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Phonological Processing in Visual Word Recognition: Behavioural, Computational & Neurocognitive Evidence

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Curriculum Vitae

Erklärung

Zusammenfassung

Die vorliegende Dissertationsschrift hat die Rolle orthographischer und phonologischer Prozesse beim Lesen mit einem spezifischen Fokus auf phonologischer Verarbeitung zum Thema. Sinnentnehmendes Lesen ist wahrscheinlich nur möglich, wenn orthographische, phonologische, syntaktische, grammatische und semantische Informationen gemeinsam verarbeitet werden. Phonologische Verarbeitung ist eine notwendige Bedingung beim lauten Lesen, da der geschriebene orthographische Kode in sein phonologisches Gegenüber übersetzt werden muss, um ein Aussprechen zu ermöglichen. Ob allerdings ein solcher Prozess beim leisen Lesen eine Rolle spielt ist immer noch unklar. Die meisten Forscher gehen davon aus, dass phonologische Verarbeitung auch beim leisen Lesen stattfindet, unklar ist jedoch zu welchem Zeitpunkt dies geschieht und wie genau dies funktioniert (Van Orden, 1987; Perfetti & Bell, 1991; Seidenberg, 1985). Die spezifische Frage ist, ob phonologische Verarbeitung notwendig ist, um lexikalischen und damit verbunden auch semantischen Zugriff zu ermöglichen.

In ihrem multiplen read-out Modell der visuellen Worterkennung (MROM) schlugen Grainger und Jacobs (1996) drei Prozesse vor, mit denen der Prozess der visuellen Worterkennung beschrieben werden kann. Ziel des Modells ist die Erklärung – auf abstrakter komputationaler Ebene – dreier universeller Phänomene der Worterkennung: des Vertrautheitserlebnisses ohne bewusste Wiedererkennung, der bewussten Identifikation, sowie der Bewusstheit, dass eine Buchstabenfolge kein Wort darstellt. Der erste Prozess beinhaltet eine kontinuierliche Vertrautheitsmessung auf der Basis der im Modell simulierten globalen lexikalischen Aktivität. In Worterkennungsaufgaben kann aufgrund dieses Prozesses eine Ja-Antwort ohne bewusste Identifikation der Stimuli gegeben werden. Beim zweiten Prozess handelt es sich um einen diskreten Identifikationsprozess auf der Basis lokaler Detektoraktivität. Stimuli werden korrekt identifiziert, wenn sie ein Entscheidungskriterium überschreiten (Identifikation). Prozess drei schließlich stellt einen Abbruchprozess dar. Eine Nein-Antwort resultiert wenn Prozesse eins und zwei bis zu einem kritischen Zeitpunkt ("deadline") keinerlei Antwort generiert haben. Prozess drei ist aktiv für Nichtwörter oder

Wörter, die keine lexikalischen Repräsentationen besitzen. Ein Hauptanliegen der in dieser Arbeit vorgestellten Studien war es zu untersuchen, ob sich für die hypothetischen Prozesse und die strukturelle Architektur komputationaler Modelle der visuellen Worterkennung wie dem MROM empirische, d.h. behaviorale und neurokognitive Evidenzen finden lassen.

Hierzu wurde die orthographische und phonologische Verarbeitung in der visuellen Worterkennung mit klassischem psycholinguistischen Paradigmen, speziell mittels der lexikalischen Entscheidungsaufgabe, des Pseudohomophon-Effekts und des Basiswort-Frequenz-Effekts genauer untersucht. Abhängige Variablen waren Reaktionszeiten und Fehlerraten, Ereignis-Korrelierte-Potentiale, sowie der Sauerstoffverbrauch von an dieser Verarbeitung wahrscheinlich beteiligten Hirnregionen (BOLD). Die neurokognitiven Methoden sollten weitere Hinweise über die kortikale Verortung/Vernetzung und den Zeitverlauf dieser Prozesse liefern.

In Studie 1 wurde mit dem MROM Stimulusmaterial generiert und anhand seiner modell-geleiteten Vorhersagen über beim Lesen beteiligte Prozesse untersucht, welche neuronalen Netzwerke am lexikalischen Zugriff beteiligt sind und wie der Zeitverlauf dieser Prozesse aussieht. Dazu wurden Ereignis-Korrelierte Potentiale verwendet. In der hirnelektrischen Aktivität wurden für das dargebotene Material zwei Komponenten gefunden. Ab ca. 350 Millisekunden nach Stimulus-Präsentation unterschieden sich Wörter von Nichtwörtern und ab 400 Millisekunden zeigte sich ein gradueller Unterschied für Nichtwörter mit unterschiedlicher Wortähnlichkeit. Diese Befunde wurden als Hinweis auf das Wirken zweier vom MROM vorhergesagter Prozesse interpretiert: i) ein Identifikationsprozess, der auf der Aktivität einzelner Wortdetektorsysteme beruht und in der Lexikalischen Entscheidungsaufgabe über eine JA-Antwort den Zeitpunkt lexikalischen Zugriffs signalisiert und ii) ein zeitlicher Abbruch-Mechanismus, der auf der globalen lexikalischen Aktivität im hypothetischen mentalen Lexikon beruht und in der Lexikalischen Entscheidungsaufgabe eine Nein-Antwort für Nichtwörter generiert. Neurokognitive Belege für die Operation des ebenfalls im MROM hypostasierten frühen Bekanntheitsprozesses wurden nicht gefunden.

In Studie 2 wurde der hirnelektrische Zeitverlauf und die Lokalisation orthographischer und phonologischer Verarbeitung anhand des Pseudohomophon Effekts mit der lexikalischen Entscheidungsaufgabe und Ereignis-Korrelierter Potentiale untersucht. Die Annahme, dass phonologische Verarbeitung relativ spät, d.h. nach semantischer oder syntaktischer Verarbeitung geschieht wurde zurückgewiesen und gezeigt, dass phonologische Vorgänge bereits ab 150 Millisekunden nach Stimulusdarbietung möglich sind. Desweiteren konnte mittels Low-Resolution-Electromagnetic-Tomography-Analysis (LORETA) gezeigt werden, dass linke temporal-parietale und rechte fronto-temporale Regionen an der Verarbeitung phonologischer Informationen auf lexikalischer Ebene zu diesem Zeitpunkt beteiligt sind.

In Studie 3 wurde wiederum orthographische und phonologische Verarbeitung mittels lexialischer Entscheidungsaufgabe, des Pseudohomophon-Effekts und zusätzlich mit dem Basiswort-Frequenz-Effekt, der eine noch spezifischere Aussage über eine potentielle Rolle phonologischer Informationen beim lexikalischen Zugriff erlaubt, untersucht. Um detailliertere Informationen über die Lokalisierung phonologischer Verarbeitung zu erhalten wurde die Methode der funktionellen Magnet-Resonanz-Tomographie (fMRT) eingesetzt. Die Ergebnisse lieferten Hinweise auf eine lexikalische Aktivierung der Basiswortrepresäntationen durch die dargebotenen Pseudohomophone, was sich am stärksten durch das Auftreten des Basiswort-Frequenz-Effekts zeigte. An der Verarbeitung phonologischer Informationen waren dabei vor allem bilaterale frontale Areale (Broca, Cingulärer Cortex) aber auch links lateralisierte parietal-temporale (Wernicke Areal, Angularer und Supramarginaler Gyrus) und occipito-temporale Areale (Fusiformer Gyrus) beteiligt.

Insgesamt sprechen meine Befunde für eine frühe Beteiligung phonologischer Verarbeitungsprozesse in der visuellen Worterkennung. Phonologische Verarbeitung unterstützt dabei den lexikalischen Zugriff auf im Gedächtnis gespeicherte Ganzwort-Repräsentationen und weist auf das Wirken eines phonologischen Rekodierungsprozesses beim leisen Lesen hin.

Summary

This thesis is about the role of orthographic and phonological processes in reading with a special focus on phonological processing. Reading for meaning is probably only possible if orthographic, phonological, syntactic and semantic information is processed simultaneously. Concerning the role of phonology most researchers agree that it takes place in both, spoken and written language processing. Phonological processing is a necessary condition in reading aloud, since the orthographic code has to be translated into its phonological counterpart. Whether such phonological recoding is also active in silent reading and when is still a matter of debate. Specifically, the question is, whether or to what extent phonological processing in silent reading aids lexical and semantic access.

In their multiple read-out model of visual word recognition (MROM) Grainger and Jacobs (1996) proposed three processes which are believed to underly visual word recognition and to account for three universal phenomena: the feeling of familiarity with a letter string (without conscious recognition), the conscious identification of a word, and the feeling that a letter string is no word. The first process computes a continuous familiarity measure on the basis of model simulated global lexical activation. In visual word recognition tasks like lexical decision this process allows for a YES-answer to a presented letter string without conscious identification. The second process is a discrete identification process on the basis of local lexical activation. Items are mapped onto stored representations and are correctly identified if a given identification criterion is reached. The third process is a temporal deadline process which elicits a NO-answer if process one and two did not generate a YES-answer until a critical moment in time since stimulus onset. This process is active for presented nonwords or unknown words which have no representation in memory. One major concern of this thesis was to seek behavioral and neurocognitive evidence for such processes and also for the structural assumptions of current computational models of visual word recognition like the MROM.

Therefore, orthographic and phonological processing in visual word recognition was investigated with standard psycholinguistic tasks and empirical effects, in particular the lexical decision task, the pseudohomophone effect and the baseword frequency effect were used to tap into these processes. Dependent variables were response times and error rates, event-related potentials, source localisation, as well as the blood-oxygen level dependent response (BOLD). The neurocognitive methods should provide additional information about the brain regions/neuronal networks likely to be involved in this kind of processing as well as their time course.

In Study 1 stimulus material supposed to cause different grades of global lexical activation was generated using simulations with the MROM. Thus, the models predictions about the processes underlying word recognition and their time course were tested. Event-related potentials were analysed to identify neuronal networks likely to be involved in lexical access. The results provide evidence for two of the three hypothetical processes predicted by the MROM. A first event-related component was obtained at around 350 msec post-stimulus sensitive to the difference between words and nonwords and was interpreted as reflecting the proposed identification process on the basis of local lexical activity and to underlie a YES-answer in the lexical decision task. A second event-related component at around 400 msec post-stimulus showed a graded effect of global lexical activity for nonwords. This component was interpreted to reflect the proposed deadline mechanism and to underlie the NO-answer in lexical decision. No evidence for an early familiarity assessement process as proposed by the MROM was obtained.

Study 2 investigated the time course and localisation of orthographic and phonological processing with the lexical decision task, the pseudohomophone effect and event related potentials. The assumption that phonological processing occurs rather late – after syntactic and semantic processing – was rejected by showing that phonological processing could influence word processing as early as 150 msec post-stimulus. Furthermore, low-resolution electromagnetic tomography analysis (LORETA) revealed that left temporal-parietal and right fronto-temporal areas were involved in phonological processing at the lexical level at this early point in time.

In Study 3 orthographic and phonological processing was investigated again with the lexical decision task and the pseudohomophone effect. Furthermore, the baseword frequency

effect was used to tap deeper into phonological processing in visual word recognition and its role in lexical access. To obtain a more detailed picture of the involved brain networks likely to be involved in reading functional magnet-resonance imaging (fMRI) was used. The measured brain activation suggested that pseudohomophones activated their baseword representations at a lexical level. This was strongly supported by the obtained baseword frequency effect. Phonological processing was mainly accompanied by bilateral frontal (inferior frontal gyrus, broca, cingulate cortex), but also left lateralised parietal-temporal (wernicke, angular and supramarginal gyrus) as well as occipito-temporal (fusiform gyrus) activation.

In sum, my results speak for an early involvement of phonological processing in visual word recognition guiding lexical access to whole-word forms stored in memory and therefore for a process of phonological recoding active in silent reading.

Ich nahm es, und ich trug es,
ich trug's zum Tisch und schlug es,
ich schlug es auf und las,
was ich herauslas, ließ
ich gerne noch für andre drin,
doch ist's in mir jetzt immerhin.
Josef Guggenmos

Introduction

As you read these words, a complex sequence of processes are active in your brain, identifying visual patterns (letters) that are mapped onto familiar units (words), the meanings of which are combined to allow comprehension. In this description, a mental dictionary or lexicon linking word forms (orthography) to word meanings (semantics) plays a central role in the reading process. However, today some fundamental questions concerning the functional and neural organisation of the mental lexicon remain unanswered. One of these questions is to what extent phonology guides lexical access by mediating between orthographic information and meaning.

Therefore, this thesis is concerned with the role of phonological processes in reading. Without the ability to read one runs into difficulties in today's societies. Reading is an advanced skill which presupposes the ability to understand language, i.e. a system of communication based upon words. Words have meanings and are combined together according to the rules of syntax to create an infinite number of sentences. Language is one, probably the outstanding ability that describes humans. Without language, life would be completely different. Our way of life would not be possible without the ability to understand spoken and written words and sentences. None of the sophisticated inventions and developments of humans were possible without using language. Our cultures originate in language: art and music is reviewed in language. Finally, literature is written language. Some scientists go even further and propose that the difference between thought and language is negligeable (the Sapir-Whorf-hypothesis; Whorf, 1964; Hunt & Agnoli, 1991). According to this hypothesis language and thought are not separated and language influences the way we think. Our concepts of the world would then be routed in language.

Language

Language can be described at a number of different levels. These levels are the fundamentals of linguistics. We differentiate between orthography (how words are spelled), semantics (meaning), syntax (word order), morphology (words and word formation), pragmatics (the study of language use), phonetics (raw language-related sounds) and phonology (sounds within a language). Semantics comprises the content of spoken or written utterances. Syntax describes the structure of utterances by providing information about word order and the function of the words in context. Pragmatics is concerned with how language is used in everyday life and with the permanent changes language is subject to. Morphology is concerned with how words are made up of simpler units called morphemes. There are two approaches to the study of sounds: phonetics and phonology. Phonology is concerned with the higher level study of sounds, whereas phonetics deals with sounds at a lower level. The central unit of phonetics is the phone, whereas the central unit of phonology is the phoneme. A phoneme is by definition the smallest meaning changing unit of a word. This thesis focusses on the role of phonological processes in the fundamental skill underlying reading: single word recognition.

Visual Word Recognition

Visual Word recognition is the process of perceiving, remembering, recognising and identifying written words, a necessary condition for reading. This process is most prominently studied in the domain of psycholinguistics which is concerned with processes of language acquisition, production and recognition. Adult humans have a passive knowledge of about thirty to fifty thousand words (Seidenberg & McClelland, 1990). Given that size, the human language processing system must be organised very efficiently to make word recognition possible. It is assumed that visual word recognition involves at least these stages of processing: (a) fixation (i.e., focussing attention) of words or individual letters, (b) perceptual identification of letter features, (c) identification of the letters themselves, (d) combination of the letters and activation of the word representation in memory, (e) activation of that words meaning and (f) activation of all other pieces of information stored about a given word. For example, at the feature level the analysis of the letter 'H' theoretically consists of extracting two vertical parallel lines connected through a horizontal line in the middle. After feature identification there is orthographic analysis leading to letter identification. Recognition of a word must be performed at the lexical level which itself theoretically reflects two processes: (a) lexical access and (b) lexical selection. Lexical access refers to the process of activating several word candidates in a hypothetical 'mental lexicon' whereas lexical selection chooses one out of these candidates for conscious identification.

The mental lexicon can be thought of as a dictionary which contains all information about the words one knows. This comprises the meaning (semantics), spelling (orthography), sound (phonology) as well as its role in sentences (syntax and grammar). Word recognition can then be viewed as a process much like using a dictionary, looking up a specific word entry gives access to its meaning, spelling etc. The mental lexicon is thought to be part of the verbal long-term memory, storing representations of words for retrieval. If word recognition proceeds without difficulty automatic lexical access, i.e. a successful activation of the mental representation of a word in long-term memory has occurred. But how exactly does this happen? How do we know that we know a word? How do we access or reconstruct its representation(s) in memory? In which way are words represented in the lexicon? Psycholinguists try to answer these questions by drawing hypotheses from theories or models which are tested in psychological experiments. In this thesis I will use behavioural, psychophysiological and neurocognitive measures to unveil how visual word recognition is performed in humans. The empirical findings will be discussed in the light of current computational models which are used to simulate the processes assumedly performed by our brain to accomplish visual word recognition.

There are a number of open questions in visual word recognition. For example, psycholinguists are not sure as to which extent the aforementioned levels function independently of each other, as to whether if there is only one flow of information from early levels of perception to higher levels of processing (bottom-up), or whether there is also flow of information from higher levels to lower levels of analysis influencing the perception of the input stream (top-down processing). There is also no agreement as to which extent phonological operations contribute to the process of visual word recognition. Introducing levels of processing in the human language system requires to specify the locus of effects found in empirical research. In the domain of visual word recognition a pre-lexical, lexical and post-lexical locus of effects has traditionally been distinguished. Pre-lexical processes occur before a word is identified. Post-lexical processes are carried out after a lexical element has been recognised. The next section deals with evidence for different levels of processing in visual word recognition.

Feature Level

In the investigation of the functioning of the feature level, confusion matrices were used to show that letters with shared features were more likely to be confused under suboptimal viewing conditions than letters that do not share features (e.g., Kinney, Marsetta, & Showman, 1966). Neisser (1967) found in a visual search task that identifying the target letter 'F' in a string of letters is easier when the surrounding letters do not share many features with the target letter for example 'U', 'O', 'M', compared to strings of letters with many shared features for example 'E', 'H', 'T'. There is also neurological evidence for an analysis of features in word recognition. Hubel and Wiesel (1962; 1968) found a neural substrate of a feature detection mechanism in the striate cortex of cats. Using the single cell recording technique they could show that when different stimuli were presented, single cells respond to different aspects of those stimuli (e.g., vertical lines, horizontal lines, motion, angles). Petersen, Fox, Snyder and Raichle (1990) extended these findings to humans. With positron emission tomography (PET) they showed blood flow changes in specific areas of the striate cortex in response to certain properties of presented stimuli.

Letter Level

Obviously letter processing is a necessary precondition for visual word recognition, as words are made up of letters. But what experimental evidence exists for that level of processing? One of the main findings for a basic role of letters in visual word recognition is the word length effect (WLE; Baddeley, Thomson, & Buchanan, 1975). Words consisting of many letters took longer to identify and to pronounce and produce longer fixation times than words made up of fewer letters (McGinnies, Comer, & Lacey, 1952; Forster & Chambers, 1973; Just & Carpenter 1980; Brown, 1987). Massaro, Venezky and Taylor (1979) showed that the position of letters in words matters, too. Using the summed positional letter frequency (the probability with which a letter occurs on a given position in a word) they showed that letter recognition performance was influenced by that positional probability. It was also found that the frequency with which letters are perceived in print does influence the response latencies in tasks with a speed component (e.g., letter matching, naming, and classification tasks), but the frequency does not seem to influence the accuracy in perceptual identification tasks. In perceptual identification tasks subjects have to recognize a presented word whose presentation is being masked by some means (fragmentation, light intensity, etc.) and signal this by pushing a button. This task allows for the elimination of disturbing effects (e.g., articulation), other than perceptual processes are excluded (Grainger & Segui, 1990). Examples for perceptual identification tasks are the fragmentation task (more and more fragments of a stimuli are revealed at different levels of presentation; Ziegler, Rey, & Jacobs, 1998) or the luminance increasing paradigm (LIP; Grainger, Carreiras & Perea, 2000). In the luminance increasing paradigm the luminance of a visual stimulus is continuously increased on a computer screen. Subjects perceive the stimulus as it becomes brighter. They are asked to stop that process at a point they believe they could identify the target. After that the target is typed into the computer. The time and accuracy of identification are measured (for a review of studies dealing with the frequency of letters see Appelman & Mayzner, 1981).

As long as 128 years ago Cattel (1885) was one of the first who investigated the role of letters in word recognition. The main question was: what are the basic perceptual units in word recognition? By trying to answer this question Cattel made a curious finding: he presented whole words and single letters to his subjects which should be pronounced and found that some words were named faster than single letters. In some cases identification of a letter took longer than the identification of a whole word (see also Erdman & Dodge, 1898). Reicher (1969) and Wheeler (1970) found a similar result in a forced choice reaction task for briefly presented stimuli. In their studies they presented a single letter, for example 'K' in a word like 'WORK' or in a nonword like 'OWRK' followed by a mask which was replaced by two adjacent single letters 'D' and 'K' as response alternatives. Identification of a target letter was faster when the target letter was presented in a word than when it was presented as a single letter or in a nonword.

This effect was named the word superiority effect (WSE). It seems that humans not only use the letter level to identify individual letters. When words and letters in words are perceived faster than single letters, could letters then be the basic units of word recognition? Findings like those of Cattel and Reicher and Wheeler motivated further research on the role of units below the word level other than the individual letters (e.g., graphemes, phonemes, morphemes or syllables) that might be functional in visual word recognition.

Word Level

In my overview on the process of word recognition I now turn from the sublexical level to the lexical level and to variables which are thought to influence the processing of whole words. The notion of the word as the basic building block in reading which aids the process of extracting meaning from print is likely due to the fact that printed words are separated through boundaries (as opposed to spoken language where no such boundaries exist, but see below). It is assumed that the human language system makes use of this boundary information and therefore develops a reading system that gives access to meaning based on the processing of whole words. Results from eye movement research (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998) showed that most words in a given text are fixated during reading, suggesting an important role of the whole-word level. Furthermore, there is also evidence that in spoken language, the interval between words is longer than between morphemes (e.g., Krueger & Vollrath, 1996). Among the variables which show influence on whole word processing, word frequency (i.e. the number of times a given word is encountered in print or speech) is the most prominent.

Word Frequency

The frequency of occurrence of words is counted for print and speech and collected in databases (e.g., CELEX; Baayen, Piepenbrock, & van Rijn, 1993; Kucera & Francis, 1967). Word frequency effects are observed in a number of tasks (lexical decision, naming, perceptual identification) and also in fixation duration measures. Words with high frequencies of occurrence are faster to identify, faster to pronounce and are shorter fixated than words with low frequencies of occurrence (Word Frequency Effect; WFE). An important question regarding word frequency is the locus of that effect. Most models of visual word recognition attribute the influence of frequency to the moment at which word recognition and lexical access happens (e.g., Balota, 1990; Balota & Chumbley, 1990; Monsell, Doyle, & Haggard, 1989; Savage, Bradley, & Forster, 1990), thus supporting the notion of a lexical effect. However, there is also evidence for other processes leading to this effect. Among these, a decision component in the lexical decision task (e.g., Balota & Chumbley, 1984; Besner, & McCann, 1987) and also a post-access component related to the generation of output of the phonological code, in particular in the naming task (e.g., Andrews, 1989; Balota & Chumbley, 1985; Connine, Mullenix, Shernoff, & Yelen, 1990) were proposed. In perceptual identification tasks sophisticated guessing mechanism were proposed by Catlin (1969, 1973) which should have more influence on perception than word frequency. Despite these different interpretations of the source of frequency effects there is little disagreement among researchers that frequency of occurrence is influencing processes involved in word recognition.

A variable that is highly correlated with word frequency is familiarity. The familiarity of a word is measured by subjective ratings. The more familiar a word is rated, the easier and faster it is processed (e.g., Boles, 1983; Connine et al., 1990; Gernsbacher, 1984; Nusbaum, Pisoni, & Davis, 1983; Nusbaum & Dedina, 1985). Familiarity effects were obtained in lexical decision and naming beyond frequency effects. Until today however, it is not clear what information subjects use to make these familiarity ratings and thus produce faster naming and lexical decision responses. In fact, there seem to be strong correlations of word familiarity with other semantic variables, such as concreteness, meaningfulness or contextual availability.

Models of Visual Word Recognition

Explaining how visual word recognition is performed by our brains is a difficult task. Psycholinguists measure human performance in a variety of different tasks like naming words, identifying words or parts of words in perceptual identification tasks or making decisions between words and nonwords in lexical decision tasks. The aim is to separate the performance aspects specific to the demands of a certain paradigm from those which are characteristic of visual word recognition per se (i.e., differentiating between task dependent and task independent processes). This multi-task approach was introduced by Jacobs and Grainger (1994) and was called the stratagem of functional overlap, implying that something like an abstract concept of word recognition can only be understood as a process common to a variety of reading-related tasks. They also transferred this idea to the field of computational models to test the performance of these models in different tasks. Thus, for a model that aims to explain how visual word recognition functions, it seems desirable to account for the results of a maximum number of paradigms and to isolate the processes common to all of these tasks.

Computational models can be seen as heuristic devices which try to answer the question of how something functions or becomes possible. The underlying ratio is derived from the functional or quasiteleological approach of scientific explanation (von Wright, 1971). In line with that approach computational models are seen as tools to gain insight in the functioning of complex cognitive systems (Marr, 1982). They help to explain how a given effect becomes possible and to falsifying the tentative functional explanation. Computational models simulate how something could function (e.g., phonological encoding in visual word recognition), but not how it necessarily must function or actually functions. Where complexity makes exact mathematical analyses difficult or impossible, computer simulations can help to guide quantitative research (Estes, 1975; Grainger & Jacobs, 1998; Jacobs & Grainger, 1994).

Today’s computational models share many basic components. The prototypical interactive-activation model (IAM; McClelland & Rumelhart, 1981) first introduced these basic components, thus a short introduction to that model and its basic functioning is in order here. The smallest entity in the IAM is a unit. An incoming signal is modified and then sent via connections to other units when a certain output threshold is reached. The amount of information represented or detected by a unit is variable. In the IAM, units are detectors for features, letters or words depending on the processing level the units are placed in. Models that represent certain units as a whole in a certain place are referred to as localist connectionist models. The units are linked by inhibitory and excitatory connections. Activation is being sent along the connections to allow the units to interact. Connections can be mono- or bidirectional. If the activation in a unit passes a given threshold, a certain amount of activation which is proportional to the unit's activation is sent to all connected units. Activation transmitted via an excitatory connection causes the activation in the receiving unit to increase by the amount of the transmitted activation. An inhibitory connection produces the contrary. Units, connections between units and transmitted activation are common to all computational models. Obviously, the way these models are built is inspired from neurophysiology: units simulating neurons and connections axons and dendrites. The activation values simulate the chemo-electrical states. But one has to take care not to mix-up the two worlds of neurophysiology and model construction: models make use of principles inspired from neurophysiology, but they remain models. The assumption behind interactive-activation models did not remain unchallenged. Several authors (Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989; Van Orden, Pennington, & Stone, 1990) claimed that there are no local units. Information is processed instead through sub-symbolic representations in the form of activation patterns which are only existent when they are activated and that this activation cannot be localised (Van Orden & Goldinger, 1994; Van Orden et al., 1990; but see Page, 2000).

Today's computational models can be divided into three main classes: (a) modular models, (b) interactive models, and (c) hybrid models. There are a number of models of visual word recognition that contribute to our understanding of that process. For space reasons I will only present one prominent example of each category to provide an overview of that model class' architecture.

Modular Models

Modular models propagate several independent processing stages (i.e., modules). Processing of information is strictly bottom-up. Units process information on each level and output is then transmitted to the next higher level. Higher level processing does not influence processing on earlier, lower levels of processing. This means, for example, that if orthographic information is processed first, it will not be influenced by phonological information processed at a later stage and phonological information can not contribute to the analysis of a given percept. This serial processing axiom implies that processing at a higher level cannot start before the previous level is completed. This should slow down processing time in modular models. Examples for modular models are the logogen model (Morton, 1969), the serial search and verification models (Forster, 1976; Paap, Newsome, McDonald, & Schvaneveldt, 1982) and also some dual-route models (Coltheart, Davelaar, Jonasson, & Besner, 1977).

Interactive Activation / Parallel Distributed Models

At the beginning of computational modelling of word recognition there was the notion of a mental dictionary that stores representations of whole-words in one or in more than one specialised lexicons (i.e., orthographic, phonological and/or semantic). An early model of that type was for example the serial search model from Forster (1973). This view was challenged by advocates of the back-propagation learning algorithm (Rumelhart, Hinton, & Williams, 1986) which was applied to a three-layered network with one hidden layer, mediating between input and output. Processing is done in parallel and in a distributed fashion. Models of that type simulate word recognition without a mental lexicon. An example for such a model is the parallel distributed model (PDP-model) of Plaut, McClelland, Seidenberg, and Patterson (1996) depicted in Figure 1.

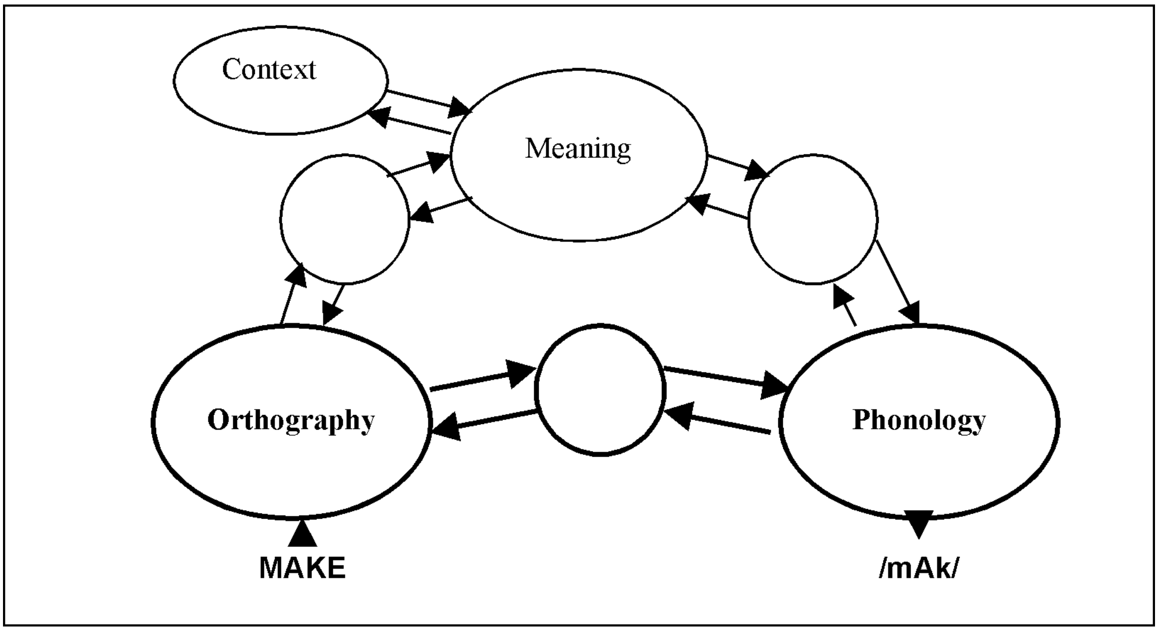

Figure 1. Basic framework for lexical processing in the PDP-model of Plaut et al. (1996) adopted from Seidenberg and McClelland (1989). The implemented model is printed in bold face type. All the knowledge the model has is represented in the connections between input and output units and in the hidden layers in between.

In contrast the localist connectionist approach states that there are local entities processing specific lexical information, "localist representations are simple processing units that can be usefully interpreted as standing for a single meaningful entity in the target world" (Grainger & Jacobs, 1998, p1). In PDP-models no specific unit represents a specific word. All information about words is represented through the connections between the elements built-in in these models. Words are represented in distributed activation patterns across many units of a certain level. In contrast to modular models, interactive and parallel distributed models assume that all levels of processing contribute in parallel to word recognition. The flow of information is bi-directional. There is also within-level inhibition (lateral inhibition): for example, if one feature is identified, other concurrent features are inhibited leading to a single, unique perception of the input (for a detailed discussion of interactive and modular models see Jacobs & Grainger, 1994). One prominent example for such a local connectionist's model is the multiple read-out model including phonology (MROM-P; Jacobs, Rey, Ziegler, & Grainger, 1998).

The MROM-P contains detectors for features, letters and words. The units are connected by inhibitory and excitatory connections. The MROM-P thus follows the system principles of interactivity and lateral inhibition and contains a phonological component which obeys to the same rules as its orthographic counterpart. The orthographic part of the MROM-P is similar to the MROM (Grainger & Jacobs, 1996). The letter detectors have excitatory connections to the phonological unit detectors. The phonological units consist of phonemes which are grouped in onset, nucleus and coda (Dell, 1988; Nuerk, Rey, Graf, & Jacobs, 2000; Plaut & McClelland, 1993; Treiman, 1992) consisting of all onsets, nuclei and codae which were contained in the 2494 monosyllabic words in the German CELEX database (Baayen, Piepenbrock, & Guliker, 1995). The connections between the letters and the phonological units are weighted by the frequency of their occurrence.

The multiple read-out mechanism of the MROM-P provides a widely accepted explanation for lexical decisions. The principle of multiple read-out states that a response in an experimental task is made, if at least one of three possible response criteria is reached. The response criteria according to Grainger and Jacobs (1996) are the following: (1) identification of words, if the activation of a lexical unit reaches an identification criterion (M-criterion) a YES-answer is produced and the word is identified; (2) a fast-guess mechanism: if the summed activation over all lexical units reaches a criterion (S-criterion) a YES-answer is elicited. The summed activation functions as a wordlikeliness value; (3) a time-out criterion (T-criterion) which is set to a fixed time value. If this value is reached before any other criterion is reached a NO-answer will be given. The T- and the S-criteria vary depending on the summed activation in the lexicon at a given point in time. The summed activation in the lexicon is a measure of stimulus familiarity: if word likeliness is high, the T-criterion will be delayed and the S-criterion is set to a lower value resulting in an easier-to-reach deadline and thus saving processing time.

The core principles of the MROM-P can be summarized as follows: (a) the multiple code activation hypothesis which states that reading includes mental processes regarding different dimensions of a word, such as orthography, phonology and semantics. The present implementation contains orthographic and phonological processes; (b) the lexical inhibition hypothesis refers to the competition (lateral inhibition) between word units within the lexical levels to allow only the best-matching word to win; (c) the variable criteria hypothesis states that the distribution of individual responses is due to a variable decision criteria. This means that each word can be described by its specific activation over time; (d) the multiple read-out hypothesis states that a response can be caused by a words match to different criteria. Figure 2 sketches the architecture of the MROM-P.

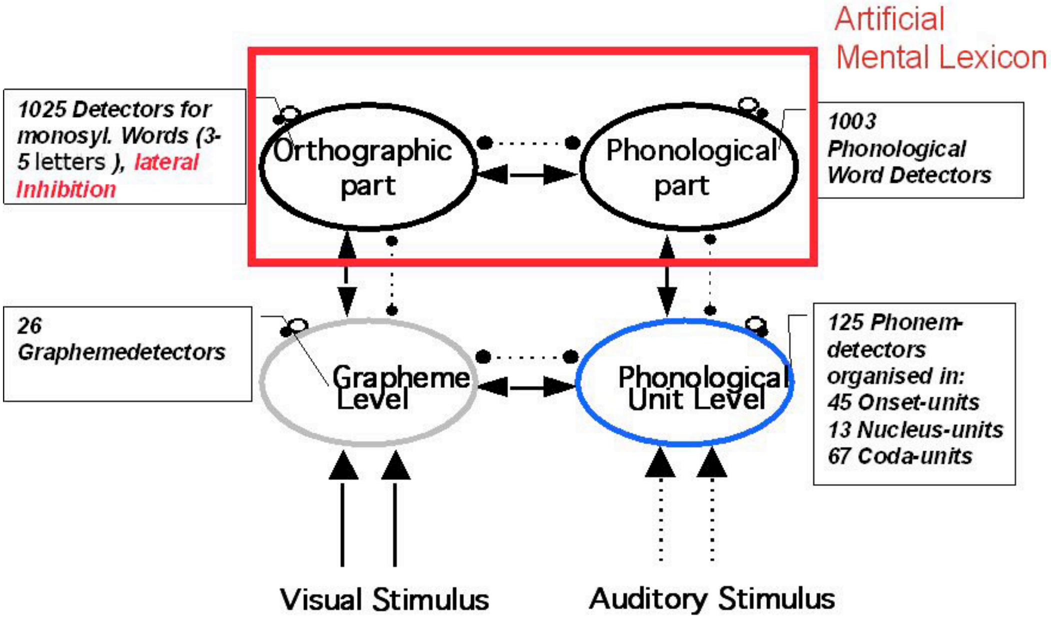

Figure 2. The MROM-P contains the same detectors for features, letters and words as the MROM (Grainger & Jacobs, 1996). Despite the orthographic part the MROM-P contains a phoneme level and also a phonological lexicon.

Hybrid Models

The Dual Route Cascaded Model (DRC; Coltheart, Rastle, Perry, Langdon, &

Ziegler, 2001) is the most popular model of visual word recognition accounting for many phenomena in clinical and developmental psychology and in psycholinguistic research. The fundamental property of the DRC (see e.g., Baron & Strawson, 1976; Paap & Noel, 1991) is that skilled readers use two different routes available for converting print into speech. A notion that led to a discussion between single-route (Seidenberg & McClelland, 1989) and multiple-route theorists which dominated part of the psycholinguistic research for the past 30 years (for a discussion of single route vs. dual route models see (Balota & Chumbley, 1984; Coltheart, Curtis, Atkins, & Haller, 1993).

The two paths from print to sound are the lexical and the non-lexical route. In the lexical route the pronunciation of a word is accessed via its lexical entry in the orthographic lexicon. The architecture is based on the IAM (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982) and the model of spoken word production by Dell (1986). The DRC claims that there is a lexical entry for every word that has been learned. The units are fully interconnected by inhibitory and excitatory connections and units within each level are lateral inhibitory connected, except for the non-lexical route which consists of simple bottom-up excitatory connections, no lateral inhibition, and most importantly, rule based processing. The DRC is thus a hybrid model. The non-lexical route acquires grapheme-phoneme conversion rules (GPCs). Unknown words and nonwords are translated from print into speech according to 39 single letter rules, 48 multi-letter rules and 14 context-sensitive rules. In German there are 45 single letter, 146 multi-letter and 38 context-sensitive rules (Ziegler, Perry, & Coltheart, 2000). These rules are position specific (e.g., initial or end position in the word). The GPCs contain one regular pronunciation for every grapheme and provide a correct pronunciation for 78.17% of the words in the English training-set. Figure 3 shows the basic architecture of the DRC.

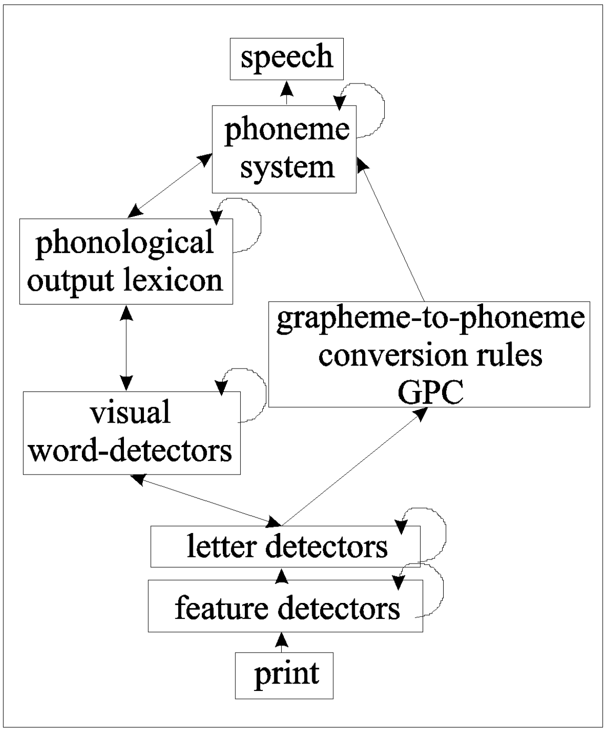

Figure 3. The architecture of the DRC. The left branch shows the lexical route and the right the grapheme-to-phoneme conversion rules (GPCs) in the non-lexical route. Both routes lead into the phoneme system, producing the pronunciation of a given word.

A presented word activates its corresponding detector (e.g., lexical entry) which then will pass activation to the corresponding representation for this entry in the phonological output lexicon. This unit then passes activation to the corresponding units in the phoneme system. The phoneme system then feeds the phonemic information to the articulatory system which controls the speech act. The lexical pathway only provides pronunciations for words, but not for nonwords which by definition lack a lexical entry. Nonwords are pronounced by applying the GPCs to the letter string. This means that the letters are entered serially into the GPC mechanism which then assigns a pronunciation to a letter or letter cluster following the conversion rules. In the current version of the DRC (Coltheart et al., 2001; Ziegler et al., 2000), the two routes are employed in parallel and both feed activation to the phoneme system. Both routes provide phonological information for nonwords, words, regular and irregular words differing only in their relative contribution.

Another example for a hybrid model was recently proposed by Zorzi, Houghton and Butterworth (1998) integrating features of PDP and DRC models. The CDP++ model is a dual-route model containing a non-lexical route based on a simple two-layer network which assembles phonological code on the basis of learned letter-phoneme connections and a quasi-lexical route based on a three-layer network representing a phonological retrieval process with a hidden unit layer as quasi-lexicon.

Phonology

Everyone who learns to read is already able to speak and to understand spoken language. The first "language code" with which children are confronted is phonological in nature. There is even evidence that deaf children make use of phonological information in reading (Hanson & Fowler, 1987; Hanson, 1989; Transler, Gombert, & Leybaert, 2001). The later mapping of letters to that primary code in reading is absolutely arbitrary, making reading a most artificial skill. Spoken language is estimated to begin 100 000 years ago – writing systems on the other hand, emerged in Mesopotamia and Egypt at the earliest around 3500 BC. Mass literacy developed only during the second half of the nineteenth century. Even today, a large percentage of the world's population is without literacy. Thus, usually children already have access to the meaning of words and their grammatical use by the time they learn to read. For the process of reading, does that mean that phonology plays also a prominent role in word recognition? Is the written, orthographic code translated back to the primary phonological code which then makes access to meaning possible? Alternatively, has every written word or a sub-component of that word direct access to meaning without activating the phonology of that word. These two hypotheses represent the extreme positions concerning the role of phonology in visual word recognition: the hypothesis of 'direct reading' without any phonological processing (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Davelaar, Jonasson, & Besner, 1977) and the hypothesis of 'indirect reading' with automatic phonological recoding through which access to meaning will be possible (Van Orden, 1987). In principle, one can imagine at least three possible routes of visual word recognition: First, translation of letters or letter clusters to sounds to gain access to the phonological form and hence to the meaning of that word. Second, clustering of letters to access the written form of the word which then is mapped to the spoken form as a whole and then mapped to meaning and third, skipping of letter to sound mapping with direct access from orthography to meaning. Figure 4 shows a framework of word recognition (Ferrand & Grainger, 1994), illustrating these three routes.

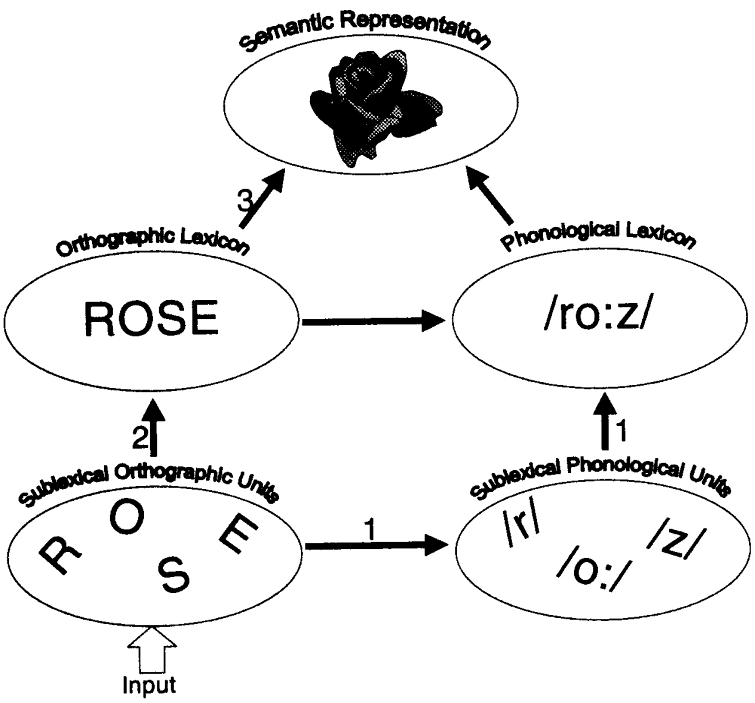

Figure 4. The framework of word recognition by Ferrand and Grainger (1994).

Presenting this far from exhaustive list of possibilities of how visual word recognition may be accomplished by the brain, we see that the process of visual word recognition is not fully understood until now. A closer look shows that word recognition despite its easiness to the experienced reader involves an enormous amount of mental work that has to be done by our brains.

Pseudohomophone Effect

Two of the three studies of this thesis made use of the pseudohomophone effect to study phonological processing. The pseudohomophone effect is the most prominent phonological interference effect providing evidence for automatic activation of phonological information in visual word recognition. Rubenstein, Lewis, and Rubenstein (1971) were the first to describe this effect. They presented pseudohomophones like 'FEAL' and pseudowords that did not sound like words 'FEEP'. The pseudohomophone 'FEAL' is phonological identical to the English word 'FEEL', but its spelling is different. The spelling control 'FEEP' is neither phonological nor orthographically identical to the real word 'FEEL'. Using the lexical decision task they found that it was harder to reject pseudohomophones than pseudowords. In subsequent research the pseudohomophone effect was found with the letter search task (Ziegler & Jacobs, 1995; Ziegler, Van Orden, & Jacobs, 1997), the naming task (Lukatela & Turvey, 1994) and the semantic categorisation task (Van Orden, 1987).

Overview

This thesis investigates the process of visual word recognition, its time course and the brain networks involved in performing the lexical decision task. The special focus is on the role of phonology in silent reading. In the lexical decision task subjects have to decide whether a presented letter string forms a word of their language (e.g., ROPE) or a nonword (e.g., BUNR). The task provides behavioural data (response times and errors) which are used to draw inferences about the processes underlying word recognition. ERPs were used as a measure of central physiological activation in reaction to the presentation of words and word like stimuli. The ERPs provide information about the time course and also about likely sources of the brain activation. Finally, fMRI was used to obtain a more detailed picture of the brain areas correlated with phonological processing. The behavioural, computational, physiological and neurocognitive findings will be discussed in the light of current models of visual word recognition.

Study 1 is concerned with the time course of lexical access of words and nonwords. Model generated stimuli of different word likeliness, theoretically eliciting graded global lexical activation are linked to lexical processing networks in the brain by using event-related potentials.

Study 2, was conducted to more directly investigate the role of phonology in silent reading using the pseudohomophone effect. Behavioural and ERP data were recorded to reveal the time course of phonological processing and LORETA was used to provide information about brain structures involved in this kind of processing.

Finally, Study 3 was conducted to provide a more detailed view about the structures involved in orthographic and phonological processing. FMRI was used to localise brain areas likely to be involved in phonological processing. The thesis ends with a general discussion and an outlook suggesting further directions of this research.

All three studies have been published or are under review in international peer-reviewed journals. Each of them was written to be understood independently. Some redundancy between them is therefore an unavoidable consequence.

Study 1

Model-generated lexical activity predicts graded ERP amplitudes in lexical decision.

Mario Braun, Arthur M. Jacobs, Anja Hahne, Brigitte Ricker, Markus Hofmann, & Florian Hutzler

Abstract

Recent neurocognitive studies of visual word recognition provide information about neuronal networks correlated with processes involved in lexical access and their time course (e.g., Holcomb, Grainger, O'Rourke, 2002; Binder, McKiernan, Parsons, Westbury, Possing, Kaufman, & Buchanan, 2003). These studies relate the orthographic neighbourhood density of letter strings to the amount of global lexical activity in the brain, generated by a hypothetical mental lexicon as speculated in an early paper by Jacobs and Carr (1995). The present study uses model-generated stimuli theoretically eliciting graded global lexical activity and relates this activity to activation of lexical processing networks using event-related potentials (ERPs). The results from a lexical decision task provides evidence for an effect of lexicality around 350 ms post-stimulus and also a graded effect of global lexical activity for nonwords around 500 ms post-stimulus. The data are interpreted as reflecting two different decision processes: an identification process based on local lexical activity underlying the 'yes' response to words and a temporal deadline process underlying the 'no' response to nonwords based on global lexical activity.

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Introduction

Studies of visual word recognition focusing on lexical access employ a number of variables assumed to influence this process (e.g., word frequency or neighbourhood density) in a number of tasks (e.g., lexical or semantic decision, naming, or perceptual identification). One of the most prominent variables is neighbourhood density, i.e. the number of orthographic neighbours, which can be generated by changing one letter of a given word, often referred to as the N-metric (Coltheart et al., 1977). When participants make a lexical decision, a standard finding is that responses to words of large neighbourhoods (so called high-N words) are faster than to words having small neighbourhoods (Andrews, 1989; Andrews, 1992; Andrews, 1997; Carreiras, Perea, & Grainger, 1997; Forster & Shen, 1996; Grainger & Jacobs, 1996; Sereno, Rayner, & Posner, 1998). On the other hand, reaction times to nonwords are slower when these stimuli have many word neighbours. Grainger and Jacobs (Grainger & Jacobs, 1996) offered an explanation for this dissociation. According to their multiple read-out model of word recognition (MROM) either of two decision criteria is in effect when subjects make decisions in the lexical decision task. The standard criterion is based on the individual word representation in memory which is activated through a presented word, triggering a positive 'yes' response for this specific item. The second criterion is based on a measure of global lexical activity representing the summed activity in the mental lexicon.

If subjects rely on the second criterion, based on global lexical activity, it is assumed that words with large number of neighbours generate increased global lexical activation in a hypothetical mental lexicon through the partial activation of all representations in memory. This extra activity could be used to make faster 'yes' responses compared to words with small number of neighbours generating lower levels of global lexical activity.

According to Grainger and Jacobs (Grainger & Jacobs, 1996) the measure of global lexical activity could also explain the inhibitory effects for 'no' responses to nonwords with large number of neighbours. In the case of 'no' decisions to nonwords the MROM has implemented a temporal deadline mechanism based on the summed lexical activity in the lexicon. It is assumed that nonwords with large number of neighbours generate also high levels of global lexical activity through the activation of word neighbour representations. This high global lexical activity prolongs the variable deadline and therefore results in slower correct 'no' responses to nonwords with large number of neighbours.

Therefore, it is possible that the opposite effects for words and nonwords having large number of neighbours in reaction times are based on the same global activity levels yielding faster responses to words and slower responses to nonwords, but are based on different response criteria (Coltheart et al., 2001; Forster & Shen, 1996; Grainger & Jacobs, 1996).

Two recent neurocognitive studies investigated this hypothesis. Both studies relate the hypothetical global lexical activity elicited by words and nonwords of different neighbourhood density to brain activity. Binder et al. (2003), using measures of blood-oxygen level dependent (BOLD) responses to letter strings in a functional magnetic resonance imaging (fMRI) study, argued: "If neighbourhood density is correlated with activation of lexical representations, and if activation of these representations is associated with neural activity, then it is reasonable to expect differences in brain activation for stimuli with large compared to small neighbourhoods, regardless of whether the stimuli are words or nonwords" (see also Graf, Nagler, & Jacobs, 2005). Unexpectedly, Binder et al. were not able to confirm this prediction and concluded that BOLD responses were not related to processing at a pre-semantic "word code" level.

The predictions of the ERP study of Holcomb, Grainger, and O'Rourke (2002) point in the same direction: "We argued that the same core mechanism, operating on global lexical activity, is at the basis of both the facilitatory and the inhibitory effects of orthographic neighbourhood density on behavioural responses to word and nonword stimuli in the lexical decision task". It was then argued that a measure of processing that directly reflects variations in global lexical activation should show effects of neighbourhood density that are in the same direction for word and nonword stimuli. In contrast to Binder et al. (2003), Holcomb et al.

found effects of neighbourhood density in lexical and semantic decision, which revealed differences in N400 amplitudes for both words and nonwords with high-N, confirming their predictions.

Both studies more or less directly tested predictions of interactive activation models of word recognition (Grainger & Jacobs, 1996; Jacobs & Grainger, 1992; Johnson & Pugh, 1994; McClelland & Rumelhart, 1981). Thus, while currently available neuroimaging evidence concerning the effects of orthographic neighbourhood density does not support predictions of localist connectionist models of word recognition, the evidence from an ERP study does so. However, both studies mentioned above tested predictions of computational models indirectly and in a dichotomous way. They used the N-metric (Coltheart et al., 1977) to operationalise the global lexical activity generated by letter strings in simulation models such as the MROM or the revised dual-route cascaded (DRC) model Coltheart et al., (2001) and 2x2 designs with stimuli of either small or large neighbourhoods. In the present study we attempted to go a step further by using graded, model-generated activity levels for words and nonwords. The idea was to directly determine the hypothetical amount of lexical activity generated by these letter strings and to examine to what extent behavioural and ERP parameters correlate with these variations of simulated global lexical activity levels.

In order to generate stimuli for the ERP study, we used the MROM as described in Grainger and Jacobs (1996) and, more recently, in Jacobs, Graf and Kinder (2003) using a lexicon of 1025 monosyllabic three-to-five letter German words. All 551 four-letter words were chosen from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) and a pool of 2000 nonwords was generated from these words by changing one, two, three, or four letters, excluding combinations that formed words. All stimuli were then submitted to the MROM to determine the overall lexical activity generated by each stimulus. As a stable measure of this overall lexical activity, the average summed lexical activation across the first seven cycles of processing was computed and transformed into z-values. 300 words and 300 nonwords were then selected so that the two resulting distributions were normal with significantly different means and equal variances. Further, the

600 stimuli were then divided into six groups according to their level of global lexical activation for purposes of analyses of variance (ANOVA). Figure 1 shows the simulated global lexical activation for two stimuli in the MROM.[1]

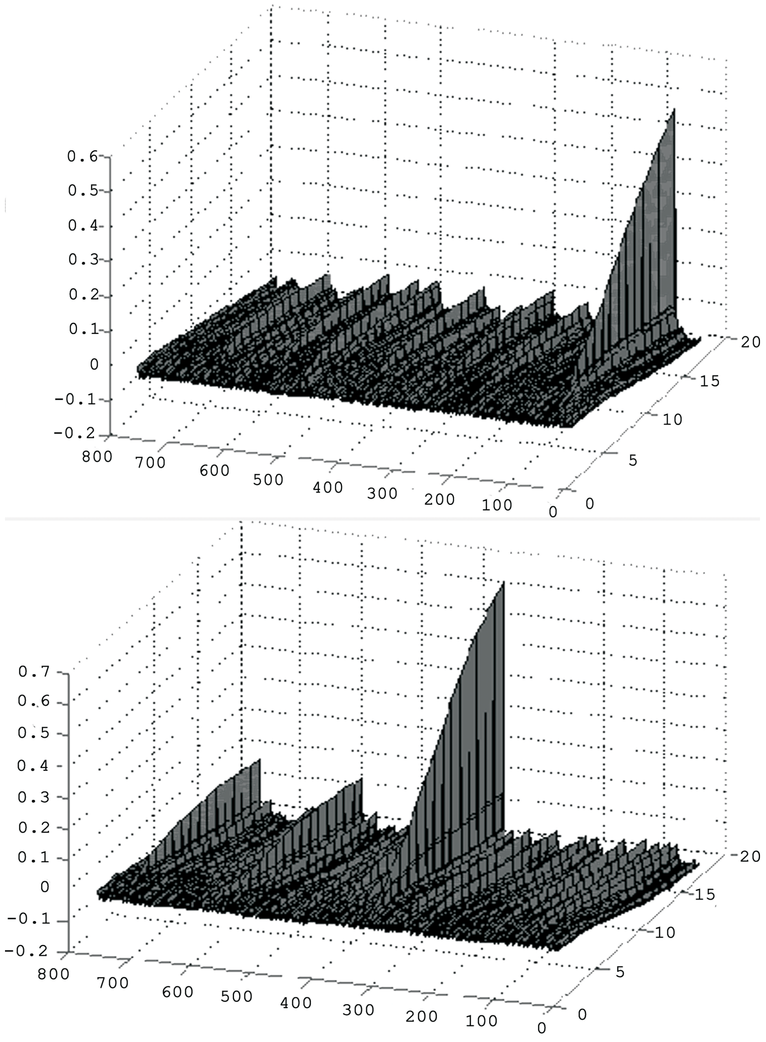

Figure 1. 3D plots of the hypothetical global lexical activation generated by two stimuli in the MROM, the nonword BFXZ (upper panel) and the word KIND (i.e., child; lower panel). The vertical (z) axis gives model activation values, the horizontal (x) axis gives a section of the extent of the lexicon (entries 1 to n), and the depth (y) axis gives cycle time.

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[1] Concerning the model-generated graded stimuli and their theoretical global lexical activation, a recent study by Graf, Nagler and Jacobs (2005) using (partial) correlation analysis with 551 four-letter German words of the CELEX database provides information on the factors that could determine global lexical activity in the model. Graf et al. found a variety of variables that affect global lexical activity significantly. The most important ones were: number of neighbors ($R^2 = .75$; $p < .001$), bigram frequency (type, i.e., the number of bigrams shared with other words; $R^2 = .58$; $p < .001$), number of higher frequency neighbors ($R^2 = .32$, $p < .001$), number of positions of higher frequency neighbors ($R^2 = .18$; $p < .001$), and log word frequency ($R^2 = .05$, $p <. 001$). This analysis shows that while it may often be reasonable to estimate global lexical activity via the N metric, other factors that may not have been controlled, such as higher frequency neighbors, might have played an important role in determining the results.

The main aim of this study was to test the prediction of the MROM according to which 'no' responses in the lexical decision task systematically depend on the global lexical activation of the nonwords, as recently suggested by Holcomb et al. (2002). If global lexical activity is correlated with brain activity, we should observe a systematic graded variation of the ERP; in particular of the N400 amplitude in response to nonwords (see Rösler & Hahne, 1992, for an overview of the language specificity of the N400). The case of words is less clear. Recent behavioural and computational data obtained in a data-limited variant of the lexical decision task showed that under such error-producing conditions, words are often correctly classified on the basis of a fast-guess, signal detection mechanism that uses global lexical activation as information (Jacobs et al., 2003).

In contrast, under the implemented presentation duration of 100 ms, a nearly-optimal exposure condition, this fast-guess mechanism should hardly operate (Jacobs et al., 2003). For such conditions, the MROM predicts that 'yes' responses are based on a high-threshold, lexical identification mechanism, which is sensitive to word and neighbourhood frequency rather than to neighbourhood density, i.e., to local lexical (i.e., single detector) activation rather than to global lexical activation (Grainger & Jacobs, 1996). We therefore expected that global lexical activation has little or no effect on ERPs to words in the current study.[2]

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[2] The results of Holcomb et al.'s lexical decision experiment showed a significant neighborhood density effect on N400 amplitude to words, but also a stronger neighborhood density effect for nonwords than for words.

Methods

Participants

Twenty-eight right-handed students of the University of Leipzig (Germany) participated in the study. All were native German speakers and were paid for their participation. All had normal or corrected to normal vision. Mean age was 23 (range: 19 to 30 years); 11 participants were male.

Experimental Materials and Procedure

Nonwords were divided into three groups of 100 stimuli with the following indices of mean global lexical activation: nonwords_1 = .16 (e.g., KNBE) nonwords_2 = .21 (e.g., BOFT), and nonwords_3 = .26 (e.g., KAND). Words were also divided into three groups of 100 stimuli according to their mean global lexical activation: words_1 = .20 (e.g., KLON - clone), words_2 = .25 (e.g., KLUG - smart), and words_3 = .30 (e.g., KIND - child).

To further characterize the processing of letter strings in visual word recognition the following variables were chosen for a later correlation analysis: global lexical activity (GLA), word frequency per million (FMIO), log word frequency (LF), neighbourhood density (N), summed frequency of neighbours (FN), number of higher frequency neighbours (HFN), summed frequency of the higher frequent neighbours (FHFN) and bigram count (BIC; the number of times the bigrams of a given word/nonword appears in other words), bigram frequency (BIF; the summed frequency of words which contain the given bigram) and bigram neighbours (BIN; number of words which differ only in one bigram).

An IBM compatible computer was used for stimulus presentation and response measurement. All stimuli were four letters long and presented in black upper case letters (4.1 * 1 cm high) on a light-grey screen. At a viewing distance of 70 cm the stimuli subtended a visual angle of approximately 0.82°. Stimuli were presented in Courier type font on a 17" colour monitor (resolution 1024 x 768 pixels, 75 Hz).

Stimulus presentation and response recording were controlled by ERTS software (BeriSoft Corp., Germany). Stimuli were presented in six pseudo-randomized blocks of 100 trials with the restriction that no more than three stimuli of one type followed each other. Participants were instructed to perform the lexical decision task as fast and as accurate as possible. Each trial consisted of a fixation point (:), shown for 400 ms, followed by the stimulus for 100 msec. Participants had to press the left button of a response pad with their left thumb, and the right button with the right thumb, the response-hands were counterbalanced across participants. Immediately after the stimulus, a mask (+++++) appeared until a response was given, but no longer than four seconds. At the end of each trial, participants were asked to rate the confidence of their response using a six-point scale, i.e. from 6 = "sure a word", over 5 = "less sure a word", to 1 = "sure a nonword". Participants were allowed to make a short break after each block of 100 trials.

Participants were given ten seconds to indicate their degree of confidence in their decision by clicking with the mouse on one of six response fields. The participants' response terminated the trial in that the next trial was initiated 1000 ms after the participants button press. Each participant completed thirty practice trials before the start of the experiment. The practice stimuli consisted of fifteen words and fifteen nonwords taken from the same pool as the experimental stimuli.

ERP Measurement

The EEG was recorded on an IBM compatible computer running on Linux OS and ANT Software (ANT Software, NL). All analyses were done using EEProbe from ANT Software. After participants took place in a comfortable chair in an acoustically shielded chamber, the EEG was recorded with an elastic cap (Easy Cap Corp., Germany), using 25 electrodes following the standard international 10-20 system referenced to left mastoid (FP1, FP2, F3, F4, F7, F8, FZ, FC3, FC4, FT7, FT8, CZ, C3, C4, T7, T8, PZ, P3, P4, CP5, CP6, P7, P8, O1, O2). The vertical EOG was recorded from electrodes placed over and below the right eye. The horizontal EOG was recorded from positions at the outer canthus of each eye.

Impedances for scalp and mastoid electrodes were less than 5 kΩ, eye electrodes below 20 kΩ. The bio signals were amplified low-pass with 30 Hz and digitized with 250 Hz continuously throughout the experiment. The 25 active sites were interfaced to a Neuroscan (Neuroscan Inc., TX, USA) amplifier system. All analyses were performed off-line after the experimental session.

Data analysis

Participants with error rates more than 17% were excluded from the analysis. No items were excluded from the analysis because of high error rates. Furthermore, responses with reaction times below 200 ms and above 2000 ms were excluded. For all stimuli and participants mean reaction time, standard deviation and percentage of errors were calculated. Trials with artifacts, such as muscle artifacts, eye movements and amplifier blocking were rejected by visual inspection; peaks that exceeded ± 40 µV were automatically rejected. Single-participant averages were calculated for each of the six conditions, followed by a grand average in a time window from 100 ms before until 1000 ms after stimulus-onset. Two negative peaks, the expected N400 and a negative component around 350 ms post-stimulus, were interesting for the present analyses. Mean amplitudes were measured in relation to a baseline 100 ms before stimulus-onset. Repeated-measures ANOVAs were performed on mean voltage data within the following two latency windows: 300 to 390 ms and 450 to 550 msec. The Geisser-Greenhouse correction (Geisser & Greenhouse, 1959) was applied to all repeated measures containing more than one degree of freedom in the numerator.

Results

Behavioural data

Nonwords_1 yielded the shortest 'no' reaction times and lowest error rates followed by nonwords of group two and three (nonwords_2, nonwords_3). For words, the pattern was reversed those having the lowest global lexical activation levels (words_1) yielded the slowest 'yes' reaction times and highest error rates followed by words with medium and high levels of global lexical activity (words_2 and words_3) see Table 1.

Table 1. Response times and error data

GLA		RT		Errors		
	N	Mean	SD	Mean	SD	%
Nonwords_1	23	758	106	6	5	9
Nonwords_2	23	791	99	9	6	11
Nonwords_3	23	826	103	13	9	16
Words_1	23	681	81	13	7	14
Words_2	23	662	78	9	5	11
Words_3	23	634	75	6	4	7

The repeated measures ANOVA for reaction times revealed effects of lexicality and a significant interaction of lexicality and global lexical activity, but no main effect of global lexical activity. Lexicality: F(1,22) = 93.54, *p* < .001, *MSE* = 609882.11, global lexical activity: F(1,22) = 2.36, *p* = .11, *MSE* = 1400.22, lexicality by global lexical activation: F (2,44) = 87.66, *p* < .001, *MSE* = 38651.54.

Individual repeated measures ANOVAs for reaction times for global lexical activity performed separately for words and nonwords reached significance: F(2,44) = 41.35, *p* < .001, *MSE* = 12822.21, and F(2,44) = 38.03, *p* < .001, *MSE* = 26863.56, respectively.

The repeated measures ANOVA for error rates revealed a significant interaction of lexicality and global lexical activity, but no main effects: lexicality: F(1,22) = < 1, *p* = .97, *MSE* = .18, global lexical activity: F(1,22) = < 1, *p* = .72, *MSE* = 3.51, lexicality by global lexical activity: F(2,44) = 34.45, *p* < .001, *MSE* = 675.48.

Individual repeated measures ANOVAs for error rates for global lexical activity performed separately for words and nonwords reached significance: F(2,44) = 19.07, *p* < .001, *MSE* = 323.45, and F(2,44) = 22.2, *p* < .001, *MSE* = 377.24, respectively.

All pairwise comparisons for reaction times and error rates performed separately for words and nonwords for the levels of global lexical activity reached significance: RT: nonwords_1 vs. nonwords_2: t(22) = -4.55, *p* < .001, nonwords_1 vs. nonwords_3: t(22) = -8.23, *p* < .001, nonwords_2 vs. nonwords_3: t(22) = -4.46, *p* < .001, words: words_1 vs. words_2: t(22) = 3.7, *p* = .001, words_1 vs. words_3: t(22) = 9.55, *p* < .001, words_2 vs. words_3: t(22) = 5.1, *p* < .001.

Error rates: nonwords_1 vs. nonwords_2: t(22) = -3.23, *p* = .004, nonwords_1 vs. nonwords_3: t(22) = -5.2, *p* < .001, nonwords_2 vs. nonwords_3: t(22) = -4.43, *p* < .001, words: words_1 vs. words_2: t(22) = 2.38, *p* = .026, words_1 vs. words_3: t(22) = 6.35, *p* < .001, words_2 vs. words_3: t(22) = 4.24, *p* < .001.

The mean confidence ratings revealed that participants were very sure of both their word and nonword decisions: for nonwords, mean ratings varied from 1.6 for nonwords_1 to 1.7 (nonwords_2), and 1.95 for nonwords_3; for words, the values were 5.3 (words_1), 5.3 (words_2) and 5.4 (words_3). Thus, the results of the confidence ratings are in line with the error analysis.

The correlation analysis for global lexical activity and other linguistic measures with reaction time yielded significant correlations for words and nonwords. For words, reaction times were affected by LF: r = -.44; p < .001, GLA: r = -.20; p < .001, N: r = -.11, p = .034, BIC: r = -.13, p = .02 and BIN: r = -.10, p = .049. For nonwords, N: r = .46; p < .001, HFN: r = .41; p < .001), GLA: r = .37;

$p < .001$, BIC: $r = .42$, $p < .001$, and also BIN: $r = .27$; $p < .001$ were correlated with reaction time. Thus, the correlation analysis revealed effects of global lexical activity for both words and nonwords.

ERP Data

22.8% of the trials were rejected because of artifacts. The ERP morphology starts with a first negative deflection occurring between 100 and 150 ms from stimulus onset (N1). This was followed by a positive deflection occurring at approximately 200 ms (P2). A significant negativity followed the P2, with a peak around 350 msec. After a short positive deflection, a later significant negativity appeared with a peak around 500 ms (N400). Figure 2 shows the grand average of all participants for the effect of lexicality and nine selected electrode positions.

Figure 2

Effect of Lexicality

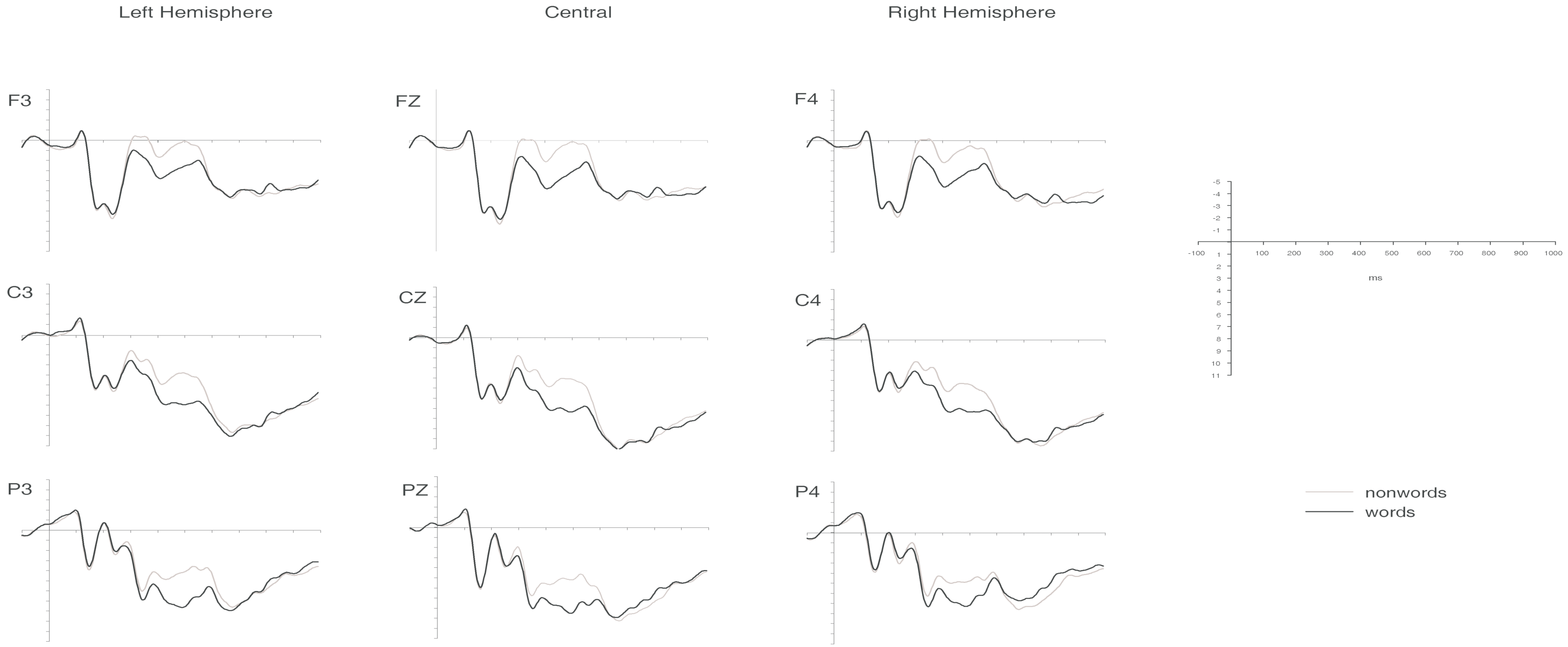

Figure 2. Grand averages for words and nonwords of all participants from selected scalp positions. Plotted in this figure are the grand averages from 23 participants for word and nonword stimuli on the 300 – 390 ms latency range. Words are represented by the black solid line and nonwords by the grey solid line.

Note that stimulus onset is represented by the vertical microvolt calibration bar and that negative voltages are plotted in the upward direction.

There was an early main effect of lexicality ranging from 300 ms to 390 ms: F(1,23) = 32.06, *p* < .001, *MSE* = 64.42, with nonwords generating greater negativity than words. Global lexical activity levels produced no effect in this time window: F(2,44) = 1.08, *p* = .35, *MSE* = 1. There was no significant lexicality by global lexical activation interaction: F(1,23) = 2.82, *p* = .07, *MSE* = 1.69.

The second negative component in the time window from 450 ms to 550 ms revealed main effects of lexicality: F(1,22) = 46.19, *p* < .001, *MSE* = 169.69 and global lexical activity: F(2,44) = 14.91, *p* < .001, *MSE* = 35.43, but no significant interaction: F(2,44) = 3.42, *p* = .059, *MSE* = 5.05. Additional performed pairwise comparisons revealed significant effects for the global lexical activity levels for nonwords: nonwords_1 vs. nonwords_2: t(22) = 4.64, *p* < .001, nonwords_1 vs. nonwords_3: t(22) = 6.18, *p* < .001, nonwords_2 vs. nonwords_3: t(22) = 3.61, *p* = .002, but not for words: words_1 vs. words_2: t(22) = 1.03, *p* = .32, words_1 vs. words_3: t(22) = 1.83, *p* = .08, words_2 vs. words_3: t(22) = 1.67, *p* = .11. Figure 3 shows the grand average of all participants for the effect of global lexical activity and nine selected electrode positions.

Figure 3

Effect of Global Lexical Activity

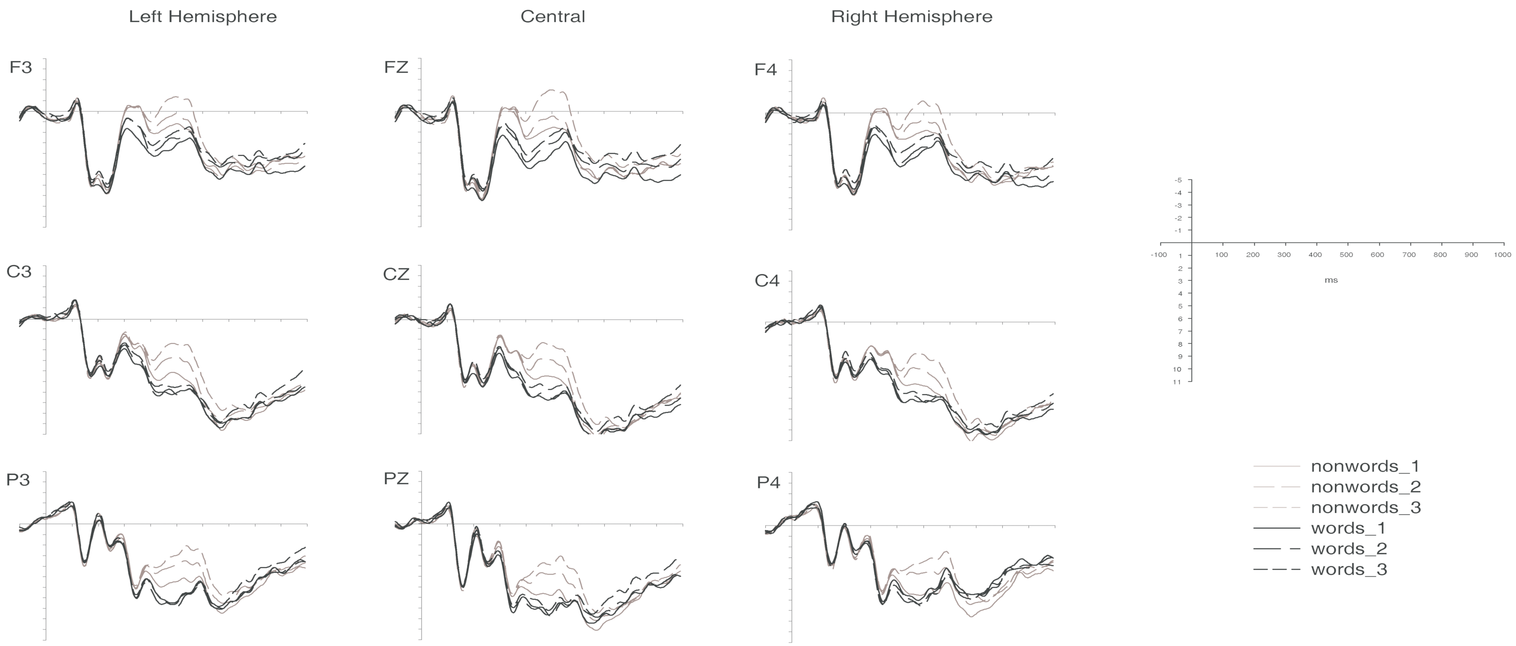

Figure 3. Plotted in this figure are the grand averages in the 450 – 550 ms latency range for the levels of global lexical activity from selected scalp positions from 23 participants. Nonword groups are represented by the following lines: nonwords_1 (most word unlike) = ——, nonwords_2 = — —, nonwords_3 = - - - . Word groups are represented by the following lines: words_1 = —— (most word unlike) = words_2 = — —, and group six words_3= - - - .

Discussion

The current study was designed as a test of two predictions of the MROM. The MROM predicts that 'no' responses to nonwords in the lexical decision task should systematically depend on global lexical activation. According to the MROM, under near optimal exposure conditions 'yes' responses should be based on a high-threshold lexical identification mechanism. Therefore, global lexical activity should have no or little effect on ERPs to words.

The behavioural analysis revealed that nonwords with the lowest level of global lexical activity yielded the fastest reaction times and nonwords with high levels of global lexical activity yielded the slowest reaction times. For words the response pattern was reversed. Thus, the behavioural analysis confirmed the predictions of the MROM that reaction times to nonwords were influenced by their different levels of global lexical activity. In contrast to the predictions of the MROM, the behavioural analysis revealed also effects of global lexical activity for words.

The ERP analysis revealed a significant negativity between 300 and 390 ms post stimulus reflecting the word-nonword difference and a later negativity between 450 and 550 ms post stimulus that reflects the global lexical activation level of nonwords, but not of words. We thus have an early categorical lexicality effect with nonwords eliciting a larger negativity than words, and a later, parametric effect of global lexical activation for nonwords, but not for words. Thus, the lexical status of the stimulus had an impact on ERPs before and possibly independently of their corresponding global lexical activation level.

Given that reaction times to words were about 130 ms faster than to nonwords, we propose that the second component (N400) reflects the operation of a temporal deadline mechanism for nonwords, as assumed by the MROM. In the MROM, 'no' responses to nonwords are computed on the basis of global lexical activation levels. The graded N400 effect therefore could reflect processing differences for nonwords of different global lexical activation levels with nonwords having high global activation levels requiring more computation compared to nonwords having low global lexical activity levels. We think that nonwords at least partially, activate orthographic and phonological similar words as well as their word neighbours and probably the semantic information associated with these words. Words in the mental lexicon should be activated stronger the more word-like the nonwords are. This, leads to higher activity in the mental lexicon making a no decision for these nonwords more difficult. Therefore, the deadline for no decisions for nonwords is prolonged. This was also supported by the results of the correlation analysis which showed that global lexical activity and also neighbourhood density are correlated with reaction times for nonwords.

The interpretation in terms of a temporal deadline mechanism is supported by a second result of our study that was not observed by Holcomb et al. (2002) and that is also important with regard to the key assumptions underlying computational models such as the MROM or the DRC. The second result is the categorical effect of lexicality on ERPs in the 300 to 390 ms time window. We think that this component reflects the threshold identification process assumed by the MROM, because the effect is independent of the global lexical activation level of both words and nonwords.

Together with the behavioural evidence (i.e., the clear categorical response sureness ratings), the absence of any modulation of this effect by global lexical activation suggests that under the present conditions a fast-guess mechanism was not involved in the computation of 'yes' responses: any significant involvement would predict graded effects of global lexical activation on ERPs. Using 100 ms presentation durations presumably suffices for allowing successful lexical access and for lexical or semantic information to become available for driving the 'yes' response. Thus, we interpret this lexicality effect, peaking at 350 ms, as the electrophysiological signature of 'yes' decisions, possibly based on a discrete (i.e., high-threshold) identification process.

Relating the observed lexicality effect at 350 ms post stimulus to the time course of visual word recognition, we propose that this is the point in time when lexical access was about to happen in our study. Previous studies revealed similar effects of lexicality (e.g. Carreiras, Vergara, & Barber, 1997; Hutzler et al., 2004; McKinnon, Allen, & Osterhout, 2003). These studies also found larger negativities for nonwords compared to words starting at 300 msec. However, most of the studies used word frequency to indicate the point in time when lexical access happens. The effects of word frequency and lexicality are mainly located in the same time range from 300 to 500 ms (e.g., Barber, Vergara, & Carreiras, 2004; Brown, Haggort, & Keurs, 1999; Johannes et al., 1996; Rugg, 1990; Van Petten & Kutas, 1990), but see (Assadollahi & Pulvermüller, 2001; Hauk & Pulvermüller, 2004; Pulvermüller, Lutzenberger, & Birbaumer, 1995; Sereno, Rayner, & Posner, 1998) for evidence of earlier lexical access.

The effects for nonwords on the N400 corroborate and extend those of Holcomb et al. (2002), who already showed that greater global lexical activity of nonwords as estimated by the N-metric lead to greater N400 amplitudes. Compared to Holcomb et al., in this study a direct parametric (three levels) output of a computational model of visual word recognition was used as an estimate of the summed activity in the mental lexicon.

Concerning the dissociation found in reaction times between words and nonwords (fast responses to words and slower responses to nonwords with many neighbours) it was hypothesized by Grainger and Jacobs (1996) that this dissociation is based on the same mechanism of global lexical activity which should be reflected in the brains activity. This was confirmed by Holcomb et al. In contrast to Holcomb et al., we did not observe an effect of global lexical activity (i.e. the summed activity of the mental lexicon) for words on the N400 component. An effect of global lexical activity for words was only found in reaction times. One possible explanation for this result could be found in the specifics of global lexical activity (i.e., words of high frequency also had a large number of orthographic neighbours).

Holcomb et al. (2002) showed that words with a large number of neighbours produced higher negative ERP amplitudes compared to those with a small number of neighbours. In contrast, ERP amplitudes in response to words of high frequency are less negative compared to low frequency words (e.g., Barber et al., 2004; Hauk & Pulvermüller, 2004; Johannes et al., 1996; Rugg, 1990). In their study, Holcomb et al. controlled their neighbourhood stimuli for frequency using words of relatively low frequency (Mean = eight per million). In our study higher levels of global lexical activity resulted in higher word frequency and also higher neighbourhood density.

Furthermore, we used words of relatively high frequency (Mean = 109 per million). Therefore, it is possible that the measure of global lexical activity comprises the effects of frequency and neighbourhood density for words. This is confirmed by the results of the correlation analysis for reaction times, where word frequency and neighbourhood density are negatively correlated with reaction times resulting in fast behavioural responses for words, but probably prevent a graded effect of global lexical activity for words in the ERP.

We are aware of the fact that our interpretations are speculative given that they more directly connect the output from a computational model to behavioural and electrophysiological data than is usually found in the literature. On the other hand, we thus take the challenge expressed by Jacobs and Carr (1995) more seriously than an increasing number of word recognition studies in the cognitive neurosciences that uses computational models of word recognition such as the MROM or DRC to interpret ERP or fMRI data in a more indirect way, that is, verbally, without actually using simulations to predict the data.

Study 2

Pseudohomophone Effects Provide Evidence of Early Lexico-Phonological Processing in Visual Word Recognition[1]

M. Braun, F. Hutzler, J. C. Ziegler, M. Dambacher & A. M. Jacobs

Abstract

Previous research using event-related brain potentials (ERPs) suggested that phonological processing in visual word recognition occurs rather late, typically after semantic or syntactic processing. Here we show that phonological activation in visual word recognition can be observed much earlier. Using a lexical decision task, we show that ERPs to pseudohomophones (e.g., ROZE) differed from well matched spelling controls (e.g., ROFE) as early as 150 msec (P150) after stimulus onset. The pseudohomophone effect occurred as early as the word frequency effect suggesting that phonological activation occurs early enough to influence lexical access. Low-resolution electromagnetic tomography analysis (LORETA) revealed that left temporo-parietal and right fronto-temporal areas are the likely brain regions associated with the processing of phonological information at the lexical level. Altogether, the results show that phonological processes are activated early in visual word recognition and play an important role in lexical access.

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Introduction

The literature on word recognition has converged to suggest that reading involves the joint activation of orthography, phonology and semantics (e.g., Seidenberg & McClelland, 1989; Grainger & Jacobs, 1996). However, there is an ongoing debate in cognitive neuroscience about the time course and the functional relationship of these reading processes. Some key questions are whether these processes are independent from each other, whether they are performed sequentially or in parallel, and whether they are automatic or strategic (Rastle, 2007). The current study aims at elucidating the time course of visual word recognition with special emphasis on the role of phonological processes.

Although phonological codes are necessarily activated in reading aloud, silent reading could in principle be performed without the processing of phonological information. Indeed, two main hypotheses have been proposed concerning the role of phonology in lexical access. The direct access hypothesis (e.g., Seidenberg, 1985) proposes a direct pathway from orthography to meaning. According to this hypothesis, phonological encoding is done rather late after meaning is accessed (i.e., post-lexically). In contrast, the phonological mediation hypothesis (Frost, 1998; Van Orden, 1987; Tan & Perfetti, 1999) suggests that semantic access depends on phonological activation. Therefore, phonology would be typically computed before people access the meaning of a word. According to this view, phonological activation occurs automatically during reading and should take place relatively early during the process of visual word recognition. Several recent computational models of visual word recognition, such as the dual-route cascaded model (DRC; Coltheart et al., 2001), the connectionist dual process model (Perry et al., 2007), the triangle model (Plaut et al., 1996) or the multiple read-out model including phonology (MROM-p; Jacobs et al., 1998) implement both a 'direct' orthographic and an 'indirect' phonological pathway to lexical access.

Phonological effects in visual word recognition were found in a number of tasks, such as backward masking (Perfetti & Bell, 1991), naming (Mechelli et al., 2007; Rodriguez-Fornells et al., 2002), lexical decision (Pexman & Lupker, 2001; Ziegler et al., 2001), sentence reading (Newman & Connolly, 2004), letter search (Ziegler & Jacobs, 1995; Ziegler et al., 1997) and also semantic categorization (Van Orden, 1987).

Phonological Effects In Behavioural Studies

In a seminal study, Perfetti & Bell (1991) reported evidence for early phonological processing in priming and backward masking. They found that briefly presented target words (e.g., MADE) that were followed by phonologically related nonword masks (e.g., MAYD) were identified more accurately as when the masks were phonologically unrelated (e.g., MARD). These effects were found for prime-target SOAs as short as 45 msec indicating early phonological processing of written words. Perfetti and Bell interpreted their phonological priming effects to be located at a pre-lexical level although they did not rule out top-down contributions of the lexical level to phonemic processing.

Indeed, Humphreys and Evett (1982) suggested that phonological priming effects result from feedback from the lexical level. They found that identification accuracy was better for targets that were presented after phonologically related primes (e.g., SHOOT - CHUTE), compared to prime target pairs that were only orthographically related (e.g., SHOOT - SHORT) or unrelated pairs (e.g., SHOOT - TRAIN). However, there was no priming from phonologically related (nonword) primes to (word) target pairs (e.g., SMORL - SMALL). More recently, however, early phonological effects in masked priming have been found even for nonword primes (e.g., Ferrand & Grainger, 1994; Ziegler et al., 2000) suggesting that phonology is computed pre-lexically.

Van Orden (1987) reported phonological effects in the semantic categorization task. Participants had to decide if a presented target was a member of a certain semantic category. This resulted in higher error rates for targets that were homophones or pseudohomophones (e.g., classifying the word ROWS or the pseudohomophone ROZE as a member of the category flowers) compared to orthographically related controls (e.g., RONE or ROBS). This result suggests an important role for phonology in accessing meaning. Van Orden proposed that reading proceeds from sublexical orthography to sublexical phonology to semantics and that recognition of printed words is mainly constrained by phonology (but see Jared & Seidenberg, 1991).

Finally, Pexman and Lupker (2001) investigated homophone effects in lexical decision. They found longer RTs for homophonic words compared to control words. The effect was typically found with low-frequency words except in the presence of pseudohomophones, in which case the homophone disadvantage emerged also for high-frequency words. The authors attributed the homophone effect to feedback from phonological representations activating two competing orthographic representations. They concluded that "readers do have little if any strategic control over the activation of phonological information of visually presented words."

Orthographic and Phonological Processing in the Brain

Several recent studies examined the time course of orthographic processing in visual word recognition using event-related brain potentials (ERPs). Hauk et al. (2006b) reported early typicality and lexicality effects at about 100 and 160 msec. Maurer et al. (2005) showed orthographic expertise effects at 170 msec. Furthermore, it has been suggested that the recognition potential (e.g., Martin-Loeches et al., 1999) in the time range from 150 to 200 msec is an index of the structural analysis of words. Sauseng et al. (2004) found that ERPs to orthographically altered word forms (e.g., taksi) differed from their base words (e.g., taxi) at around 160 msec. Finally, Bles, Alink and Jansma (2007) used a gating paradigm to investigate cohort size reduction in visual word recognition and reported a relatively early P2 (212-280 msec) in response to presented letter strings assumed to give rise to the activation of lexical candidates. The obtained P2 was interpreted as reflecting the amount of inhibition of words that mismatches the orthographic/phonological input. Other ERP studies reported later orthographic effects (e.g., Braun et al., 2006; Hutzler et al., 2004).

Concerning effects of phonological processing in visual word recognition the ERP evidence is rather mixed. Ziegler et al. (1999) asked participants to perform a visual semantic categorization task identical to the one used by Van Orden (1987). They found no early effects of phonology in ERPs. Simon et al. (2006) found phonological effects at 320 msec (N320) in a lexical decision task. Interestingly, the phonological effects were modulated by the orthographic transparency of the writing system pointing to a pre-lexical locus of the effect. Grainger et al. (2006) reported visual phonological priming effects at 250 msec in a primed semantic categorization task. Finally, a few other studies point to relatively early phonological influence on the P/N200 components (Barnea & Breznitz, 1998; Kramer & Donchin, 1987; Niznikiewicz & Squires, 1996). However, these findings are not without problems. For example, Kramer and Donchin (1987) and Barnea and Breznitz (1998) used rhyme judgments to address the role of phonology, but rhyme judgments necessarily require the activation of phonology and therefore do not directly speak to the issue of automatic phonological activation during silent reading. Niznikiewicz and Squires (1996) reported an enhanced N200 to homophones which they interpreted as reflecting sublexical conflict between orthography and phonology. However, there is no sublexical conflict when processing homophones unless one assumes that conflict arises because lexical phonology feeds back to competing orthographic representations, thus diluting the strict distinction between sublexical and lexical processing. The majority of research, however, has located phonological processing on the N400 component or even later (e.g., Bentin et al., 1999; Proverbio et al., 2004; Rugg, 1984; Newman & Connolly, 2004). The currently available ERP data do not allow us to decide whether phonological information is necessarily involved in visual word recognition and whether it is computed before lexical access.

The Present Study

It is surprising that none of the above mentioned studies has used the well known pseudohomophone effect (PHE) in lexical decision, which is the classic marker effect for phonological activation in visual word recognition (Jacobs & Grainger, 1994). The PHE (Rubenstein et al., 1971) reflects the fact that nonwords which sound like words but are spelled differently (e.g., feal) result in slower response latencies compared to spelling controls which do not sound like words (e.g., feep). The PHE has been used as a marker for phonological activation in reading development (Goswami et al., 2001) and it provides major constraints for computational models of visual word recognition (see Jacobs & Grainger, 1994; Seidenberg et al., 1996; Ziegler et al., 2001).

The standard explanation for the PHE is that a given pseudohomophone contacts the lexical entry of its phonologically identical base word in the mental lexicon. In the context of lexical decision, the phonological lexicon 'signals' the presence of a word, whereas the orthographic lexicon 'signals' the absence of a word. It is assumed that resolving this conflict takes time and therefore participants show longer latencies when rejecting pseudohomophones compared to spelling controls (Jacobs et al., 1998; Ziegler et al., 2001). While early research raised the possibility that PHE might be due to an orthographic similarity confound (Martin, 1982), subsequent research clearly showed that the PHE is not due to orthographic confounds (e.g., Rastle & Brysbaert, 2006; Ziegler et al., 2001).

In the present study, we used the PHE as a marker for phonological activation and the effect of word frequency as marker for lexical access. There is evidence for very early lexical processing at around 100 msec after stimulus presentation (e.g., Pulvermüller et al., 2001; Sereno et al., 1998; 2003), although most studies locate lexical access later at around 250 msec (e.g., Cohen, et al., 2000; Grainger et al., 2006; Nobre et al., 1994). The earliest effects of word frequency were found at around 130 msec (e.g., Assadollahi & Pulvermüller, 2001; Sereno et al., 1998, 2003; Dambacher et al., 2006), but the majority of studies locate it later, at around 300 msec (e.g., Polich & Donchin, 1988; Van Petten & Kutas, 1990).

In summary, the aim of the current study was to find evidence for an early phonological activation in visual word recognition. Most previous studies used explicit phonological tasks, such as rhyme judgments (e.g., Barnea & Breznitz, 1998; Kramer & Donchin, 1987; Rugg, 1984), to amplify phonological processing. In contrast, we investigated phonological effects in the lexical decision task, a classic visual word recognition task that could in principle be solved without phonological processing (Grainger & Jacobs, 1996). If phonological processing constrains lexical access, as suggested by the phonological mediation hypothesis, then the PHE should occur together with or before the word frequency effect. If phonology is processed post-lexically, as suggested by the direct access hypothesis, then the PHE should occur after the word frequency effect. In addition, low-resolution electromagnetic tomography analysis (LORETA) was carried out to provide information about possible cortical generators of the ERP distributions recorded at the scalp.

Material and Methods

Participants

Twenty-five right-handed students (five men, mean age 21.3 years) from the Freie Universität of Berlin participated in the study. All participants were native German speakers and had normal or corrected to normal vision. After the analysis of response time data seven participants were excluded because they showed no effects of word frequency (2), lexicality (3) or phonology (2) in the response time analysis. This resulted in a total of 18 sets of EEG data, which were subjected to ERP and LORETA analyses. No items were excluded from the analyses. Response times below 200 msec and above 2000 msec were excluded (5.91%).

Stimuli

The critical stimulus set contained 480 stimuli (240 words and 240 nonwords). Of the 240 word stimuli 120 served as fillers. Of the 240 nonwords half were pseudohomophones and half were spelling controls. To rule out orthographic similarity as the basis of the PHE, we constructed our pseudohomophones and spelling controls according to the criteria put forward by Martin (1982). That is, both item types were generated from the same base words, changing only one letter at the same position and controlling for frequency and number of neighbours. In addition, the two groups were matched for sublexical measures of bigram frequency (type and token, see Table 1).

Pseudohomophones had the same phonology but differed in spelling from their base words. Spelling controls differed in spelling and in phonology from their base words. For example, the pseudohomophone 'SAHL' and the spelling control 'SARL' were derived from the base word 'SAAL' (room). Of the pseudohomophones and the spelling controls one-third had three, one-third had four and one-third had five letters. Half of the pseudohomophones and spelling controls of each length were derived from high frequency base words (more than 20 occurrences per million, mean 820.54). The other half of the pseudohomophones and spelling controls were derived from base words of low frequency (less than 20 occurrences per million, mean 5.88). Frequency estimates were taken from the CELEX database (Baayen et al., 1993).

Of the 120 word stimuli, one-third had three, one-third had four, and one-third had five letters. One half of the word stimuli of each word length were of high frequency (more than 11 occurrences per million, mean 1405.62) and the other half were of low frequency (less than 11 occurrences per million, mean 3.93). The word stimuli were matched on bigram frequency (type count), number of syllables (Syl), number of neighbours (N), summed frequency neighbours (FN) and number of higher frequency neighbours (HFN).

Table 1: Matched variables for pseudohomophones, spelling controls and words

	Frequency		
	low	high	mean
	Pseudohomophones		
BF (type)	31.5	41.6	36.6
BF (token)	2698.9	3633.9	3166.4
N	3.4	3.5	3.5
	Spelling Controls		
BF (type)	31.5	41.6	36.6
BF (token)	4857.5	8440.7	6649.1
N	3.4	3.6	3.5
	Words		
BF (type)	46.9	57.3	52.1
FN	188944.2	39777.0	114360.6
HFN	1.9	0.8	1.35
N	3.3	4.3	3.8
Syl	1.5	1.3	1.4

Note. BF (type) = summed positional bigram count; BF (token) = summed positional bigram frequency count; N = number of neighbours; FN = summed frequency of orthographic neighbours; HFN = number of higher frequency orthographic neighbours; Syl = number of syllables.

Procedure

Participants were seated in front of a computer screen at a distance of approximately 50 cm and were given written instructions. They were told that they were going to see letter strings, some of which were German words and some were nonwords. Participants were instructed to indicate by button press as fast as possible, but not to the expense of accuracy whether the stimulus was a German word or not using the left and right index finger of the respective hand. The response hands were counterbalanced across participants. A short break appeared after every 40 trials. Participants received 30 practice trials to familiarize them with the task. The experimental trials were presented in randomized order for each participant. Each trial began with a 700 msec presentation of a fixation mark (+) in the centre of the screen. The fixation mark was replaced by the stimulus, which remained on the screen until button press. After the stimulus, a mask of hash marks (######) indicated the possibility for eye blinks for another 1.5 seconds. After a blank screen of 500 msec the next trial started with the fixation mark. The stimuli were displayed in white on a black background. They were typed in upper case letters using a standard (Times New Roman) 20 pt font. The whole experiment took about 60 minutes.

ERP Recordings and Analyses

Brain electrical activity was continuously recorded from 27 Ag/AgCl scalp electrodes placed on an elastic cap (EASYCAP, No. 22, Germany) referenced to linked left and right mastoids. A sampling rate of 250 Hz and a low-pass filter of 50 Hz were applied. To monitor eye movement artifacts, the horizontal EOG was recorded from the inner and outer canthus of each eye. The vertical EOG was recorded from electrodes placed above and below the right eye. Impedances for scalp and mastoid electrodes were less than 5 kΩ, eye electrodes below 20 kΩ. All signals were written continuously to hard disk. The EEG was analyzed off-line after the experimental session with BrainVision Analyzer Software (BrainProducts, Germany). EEG waveforms were filtered with a bandwidth from 0.1 to 30 Hz (24 dB/oct) and controlled for artifacts using an automatic rejection procedure, rejecting trials with peak-to-peak potential differences larger than 75 µV in at least one EEG channel followed by a visual inspection. Single participant averages were calculated for each of the conditions followed by a grand average in a time window from 200 msec before and until 800 msec after stimulus onset.

In the averaged data, for each channel the mean amplitude of a 100 msec pre-stimulus interval was subtracted from all sampling points for baseline correction. Root Mean Square (RMS) was used to extract time windows with the highest difference between conditions, which were then chosen for further analyses. All subsequent analyses were calculated for mean amplitudes of the selected time windows.

LORETA

Low-resolution electromagnetic tomography (LORETA) was used to determine the possible underlying cortical generators of the surface activity. LORETA identifies the most plausible three-dimensional distribution of cortical current density, which accounts for a certain observed scalp EEG signal with an average localization error of approximately 10 mm (Cuffin et al., 2001). To determine statistical significances of differences in regional neural activity between the experimental conditions, statistical nonparametric mapping procedures as implemented into the LORETA software package were used. Paired t-tests (two-tailed) comparing the conditions were computed on a voxel-by-voxel basis over all participants. Voxels with t-values above the critical threshold ($p < .05$, one-tailed) were considered to represent regions of differential activation.

Results

Response times

Response times were submitted to three ANOVAs: a 2 x 2 repeated measurement ANOVA with phonology (pseudohomophones vs. spelling controls) and base word frequency (high vs. low) as within-subject factors as well as two one-way ANOVAs – one with word-frequency (high vs. low) and one with lexicality (nonwords vs. words) as within-subject factor. In case of significant effects in the subject-based (F1) analysis, the generalisability over stimulus material was examined with items as cases (F2), whereby all factors were between-item factors. In case of violation of sphericity, dfs were adjusted according to the Greenhouse-Geisser correction.

As evident from Table 2, a main effect of phonology in the two-way ANOVA revealed that responses to pseudohomophones were 32 msec slower than those to spelling controls [F1(1,17) = 53.64, p < .001, MSE = 42483; F2(1,118) = 22.17, p < .001, MSE = 166467]. A main effect of base word frequency indicated that response times for items derived from low frequency base words were slower than response times for items derived from high frequency base words [F1(1,17) = 20.84, p < .001, MSE = 9958; F2(1,118) = 4.71, p = .031, MSE = 35366]. The phonology by base word frequency interaction was not significant [F1(1,17) = 2.57, p = .13, MSE = 4706; F2(1,236) = 2.21, p = .14, MSE = 16583].

The first one-way ANOVA revealed a main effect of word-frequency indicating that high frequency words were responded to faster than low frequency words, [F1(1,17) = 21.03, p < .001, MSE = 69192; F2(1,118) = 8.52, p < .001, MSE = 365300]. The second one-way ANOVA revealed a main effect of lexicality showing that the lexical status of the items did affect response times: nonwords were responded to 100 msec slower than words, [F1(1,17) = 15.09, p = .001, MSE = 149026; F2(1,233) = 62.10, p < .0001, MSE = 563688]. An inspection of Table 2 reveals that accuracy of responses was close to ceiling for all types of stimulus material; error rates were therefore not submitted to statistical analysis. In sum, the response time analysis revealed the expected effects of phonology, base word frequency, word frequency and lexicality.

Table 2: Reaction time means and Error rates for pseudohomophones, spelling controls and words.

	Reaction Time (msec)		Error rates (%)	
	(baseword) Frequency		(baseword) Frequency	
	low	high	low	high
PH	882.44	842.75	2.11	1.50
SC	817.69	810.33	1.39	1.37
WO	746.41	700.10	4.03	1.33

Note. PH = pseudohomophones, SC = spelling controls and WO = words

ERPs

20.3% of the trials were rejected because of artifacts. The ERP morphology starts with a negative deflection occurring at 100 msec from stimulus onset (N1). This was followed by a positive deflection peaking at approximately 200 msec (P200). A negativity followed the P200, with a peak around 400 msec (N400). Figure 1 shows response time means and standard errors as well as RMS of all participants for the different conditions over all electrode positions and the voltage curves for selected electrode positions for the effects of phonology, word frequency and lexicality.

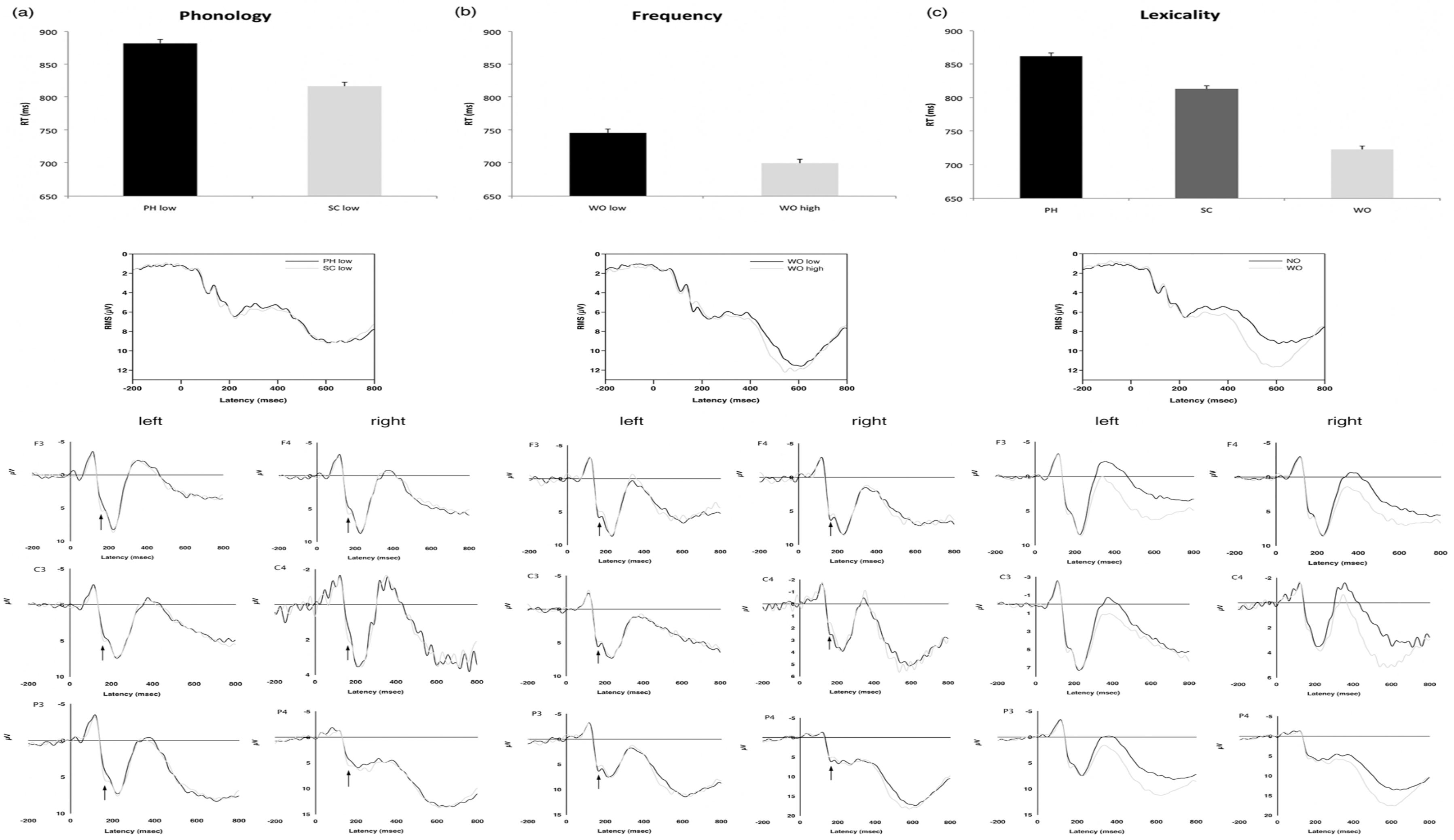

Figure 1. Response time means and standard errors as well as root-mean-square (RMS) and voltage curves for selected electrodes for the effects of (a) phonology, (b) word frequency and (c) lexicality.

Note. WO = words, NO = nonwords, PH low = low frequency pseudohomophones, SC low = low frequency spelling controls, WO low = low frequency words, WO high = high frequency words.

Statistical analyses comprised a stepwise procedure. First, global analyses for the respective conditions were calculated by means of repeated measurement ANOVAs with hemisphere (left vs. right) and region (frontal vs. posterior) as within-subject factors. In case of a significant main effect or interaction, separate repeated measurement ANOVAs for each of the four regions (frontal left and right, posterior left and right) were calculated. If this quadrant analysis resulted in significant effects, paired t-tests for single electrodes for the different conditions in the respective quadrants were computed.

For the different experimental conditions, three time windows were chosen for analyses: 152 to 184 msec (low frequency pseudohomophones vs. low frequency spelling controls), 152 to 216 msec (low frequency words vs. high frequency words) and 260 to 760 msec (low frequency pseudohomophones and spelling controls vs. high and low frequency words).

The ERP data revealed an early difference between pseudohomophones and spelling controls for low frequency items in the time window from 152 to 184 msec. For the low-frequency items only, the repeated measures ANOVA revealed significant effects of phonology [F(1,17) = 5.85, p = .027, MSE = 17], of region [F(1,17) = 23.28, p < .001, MSE = 330] and a marginally significant phonology-by-region interaction [F(1,17) = 3.97 p = .063, MSE = 2]. The subsequent quadrant ANOVAs revealed main effects of phonology and electrodes for left and right posterior regions, but not for frontal regions. Left posterior: phonology [F(1,17) = 8.20, p = .011, MSE = 36] and electrodes [F(4,68) = 44.38, p < .001, MSE = 690]. Right posterior: phonology [F(1,17) = 9.04, p = .008, MSE = 38] and electrodes [F(4,68) = 33.27, p < .001, MSE = 441].

In the time window from 152 to 216 msec, low frequency words differed from high frequency words. The repeated measures ANOVA revealed significant effects of frequency [F(1,17) = 7.66, p = .013, MSE = 29], of hemisphere [F(1,17) = 5.55, p < .031, MSE = 11] and region [F(1,17) = 6.88, p = .018, MSE = 11] as well as a significant interaction of hemisphere and region [F(1,17) = 22.21, p < .001, MSE = 25]. The subsequent quadrant ANOVAs revealed main effects of frequency and electrodes for all four quadrants and a significant interaction of frequency-by-electrodes at left anterior sites. Left anterior: frequency [F(1,17) = 5.67, p = .029, MSE = 23], electrodes [F(3,51) = 20.46, p < .001, MSE = 319], frequency-by-electrodes F(3,51) = 3.24, p = .049, MSE =

3]. Right anterior: frequency [F(1,17) = 7.08, p = .016, MSE = 22], electrodes [F(3,51) = 16.69, p < .001, MSE = 593]. Left posterior: frequency [F(1,17) = 6.10, p = .024, MSE = 34], electrodes [F(4,68) = 6.44, p = .007, MSE = 95]. Right posterior: frequency [F(1,17) = 7.60, p = .013, MSE = 41], electrodes [F(4,68) = 10.77, p < .001, MSE = 54].

Nonwords differed from words in the time window from 260 msec to 760 msec from peaking at 400 msec (N400). The repeated measures ANOVA revealed significant effects of lexicality [F(1,17) = 21.01, p < .001, MSE = 160], of hemisphere [F(1,17) = 16.12, p = .001, MSE = 43] and region [F(1,17) = 53.58, p < .001, MSE = 269] as well as a significant interaction of lexicality and region [F(1,17) = 21.43, p < .001, MSE = 1.83]. The subsequent quadrant ANOVAs revealed main effects of lexicality and electrodes for all four quadrants and a significant interaction of lexicality-by-electrodes at left anterior and right posterior sites. Left anterior: lexicality [F(1,17) = 21.15, p < .001, 136 = 23], electrodes [F(3,51) = 21.48, p < .001, MSE = 639], lexicality-by-electrodes F(3,51) = 7.28, p = .006, MSE = 12]. Right anterior: lexicality [F(1,17) = 18.84, p < .001, MSE = 97.88], electrodes [F(3,51) = 11.28, p < .001, MSE = 290]. Left posterior: lexicality [F(1,17) = 23.38, p < .001, MSE = 248], electrodes [F(4,68) = 29.09, p < .001, MSE = 95]. Right posterior: lexicality [F(1,17) = 21.32, p < .001, MSE = 242], electrodes [F(4,68) < 29, p < .001, MSE = 416]. Table 3 shows significant electrodes for the effects of phonology and frequency in the corresponding time windows.

Table 3: Electrodes showing differences for phonology (pseudohomophones vs. spelling controls) and word frequency (low vs. high) effects, p < .05

Region	Phonology (152-184ms)				Frequency (152-216ms)		
left anterior	-	-	-	-	F3	F7	-
right anterior	-	-	-	-	F8	FC6	-
left posterior	CP1	CP5	P3	P7	CP1	P3	P7
right posterior	CP2	P4	P8	O2	CP6	P8	-

Note. Electrode labels refer to electrodes, which showed significant differences (p < .05) after significant ANOVAs in the previous quadrant analysis for the selected conditions and time windows. Empty cells refer to non-significant (p > 1) effects.

Source Analysis

LORETA analysis was applied to find possible underlying generators of the effect of phonology in the time window from 152 to 184 msec. Inspection of the mean activity for pseudohomophones and spelling controls revealed the highest activity in the medial frontal gyrus (MFG, BA6; x = -3 y = -4 z = 64) for both conditions followed by activity in the posterior central gyrus (PCG, BA40; x = -59 y = -25 z = 22). The LORETA images of current density distributions for the effect of phonology were separately averaged across subjects for the respective conditions and the differences between conditions were examined. Statistical significance of the differences in the distributions between conditions was assessed by voxel-by-voxel t-tests of the LORETA images, using the current density with no data transformation and subject-wise normalization separately for both conditions. The voxel-by-voxel p-values were corrected for multiple testing according to Nichols and Holmes (2002). The analysis revealed a highly significant difference for the contrasts of pseudohomophones and spelling controls in the left supramarginal gyrus (SMG, BA40; x = -52 y = -53 z = 36) [t = -3.45, p = .003] and a difference in the right superior temporal gyrus (STG, BA22; x = 53 y = 3 z = 8) [t = 2.99, p = .036]. Figure 2 (a) and (b) show the results of the LORETA analysis for low frequency pseudohomophones and low frequency spelling controls.

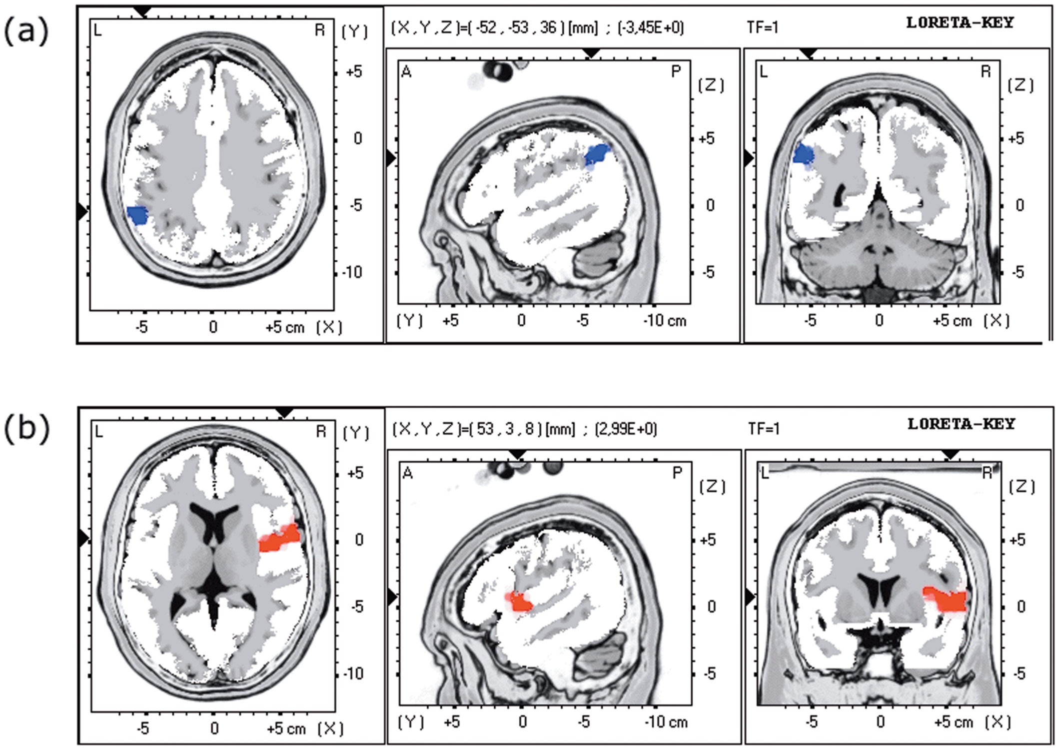

Figure 2. Results of the low LORETA t-statistics comparing event related potentials time locked to the presentation for the contrast of low frequency pseudohomophones vs. low frequency spelling controls (a) left temporo-parietal (SMG) activation (b) right fronto-temporal (IFG, STG, insula) activation. The images show LORETA slices in Talairach space for the estimated source distributions of activation differences.

Discussion

The PHE was used to investigate early automatic phonological activation in visual word recognition. The behavioural results clearly replicate those from previous studies reporting slower response times and higher error rates for pseudohomophones compared to spelling controls in lexical decision. Therefore, these results point to an important role of phonological processing in visual word recognition. The PHE was strongest for items derived from low-frequency base words, a finding that is consistent with previous research (e.g., Ziegler et al., 2001; Rubenstein et al., 1971). This pattern can be understood in the context of current dual route models (Coltheart et al., 2001; Perry et al., 2007). In these models, there is a fine balance between orthographic (lexical) and phonological (nonlexical) processing. In the case of pseudohomophones, there is conflict between the two routes because the phonological route provides evidence in favour of word representations, whereas no symmetrical activation is found in the orthographic lexicon. Thus, the orthographic route needs to inhibit the 'misleading' information from the phonological lexicon. In the case of a low-frequency base word, orthographic activation will be weaker than in the case of a high-frequency base word, thus giving more time to the phonological route to boost its activation. As a consequence, pseudohomophones derived from low-frequency base words will provide stronger phonological activation, thus causing greater conflict within the system than pseudohomophones from high-frequency base words.

Effects of word frequency are taken as an upper limit for lexical access (e.g., Forster & Chambers, 1973; Rubenstein et al., 1970; Sereno et al., 1998; Hauk & Pulvermüller, 2004, but see Balota & Chumbley, 1984 for a different view). Lexical access involves the matching of features extracted from the stimulus to internal representations of words. Current models of visual word recognition (e.g., DRC or MROM-p) implement frequency sensitive representations. Word frequency is believed to determine the availability of lexical representations by affecting the resting levels of these representations. Therefore, according to these models, high frequency words are responded to faster in lexical decision because their representations have higher resting levels compared to low frequency words thus giving rise to a head start. Responses to high frequency words in our study were about 46 msec faster than those to low frequency words. We interpret this word frequency effect to reflect lexical access which is faster for high than for low frequency words.

Previous research suggested that phonological processing in visual word recognition occurs rather late, typically after semantic or syntactic processing (Bentin et al., 1999; Rugg, 1984; Ziegler et al., 1999). In contrast, the present results clearly show that phonological activation in visual word recognition can be observed much earlier. Indeed, in the present study, ERPs to pseudohomophones derived from low frequency base words differed as early as 150 msec (P150) after stimulus onset compared to well-matched spelling controls. Spelling controls evoked a more positive peak than pseudohomophones which is most likely because the mismatch between orthography and phonology is more easily detected in spelling controls than in pseudohomophones.

We consider this P150 as the brain electrical response to the conflict between orthographic and phonological word representations in memory. Pseudohomophones activate their corresponding phonological word representation. There is conflict because the orthographic representation does not match the phonological representation. In contrast, neither words nor spelling controls do produce such a conflict. In the case of words, there is no conflict because the orthographic representation matches the phonological representation. In the case of spelling controls, there is no conflict because spelling controls do not fully activate existing phonological representations.

Time course analyses clearly showed that the phonological marker (i.e., the PHE) co-occurred with the lexical marker (i.e., the word frequency effect) – these effects were observed in nearly the same time window (152 to 216 msec). This finding adds further support to the claim that phonological activation occurs early enough to affect lexical access. Indeed, Hauk and Pulvermüller (2004) also reported word frequency effects in a very similar time window between 150 and 200 msec (see also Assadollahi & Pulvermüller, 2001; Sereno, Brewer, O'Donnell, 2003; Dambacher et al., 2006, but see Polich & Donchin, 1988; Van Petten & Kutas, 1990; Rugg, 1990; Pulvermüller et al., 2001 for later effects of word frequency).

Similarly, Sauseng et al. (2004) reported early differences between pseudohomophones and words in a frontal and posterior P/N160 component post-stimulus. They proposed that at this point in time pseudohomophones contact the stored visual orthographic representations of words. Furthermore, the orthographic deviation of the pseudohomophones from their base words was thought to result in the reduction of P160/N160 amplitudes. Finally, Hauk et al. (2006a) reported lexical and semantic processing as early as 160 msec employing linear regression analysis on neurophysiologic data from a visual lexical decision task.

These findings suggest that lexical access from written words can occur as early as 200 msec after stimulus presentation. Words in our study differed from nonwords (pseudohomophones and spelling controls) in the time window from 260 to 760 msec after stimulus presentation peaking at 400 msec (N400). N400 activity modulation is mostly found when the eliciting stimulus is semantically evaluated following the prior activation of a context or by presenting sentences containing the target (e.g., Kutas & Hillyard, 1980) which is not the case in the present study.

If we take the early frequency effects as a reliable index for lexical access, we suggest that later occurring lexicality and frequency effects peaking around 400 msec post-stimulus might reflect reprocessing or semantic integration, consistent with a post-lexical interpretation of mechanisms underlying the N400 (e.g., Holcomb, 1993; Brown, & Hagoort, 1993).

The source analysis supports the results of the ERP analysis in suggesting an early influence of phonological information in visual word recognition. The contrast of pseudohomophones and spelling controls revealed the largest differences in a left temporo-parietal area including the supramarginal gyrus (SMG, BA40) and in a right fronto-temporal area at the border of the inferior frontal gyrus (IFG, BA44,45), the insula (BA13), the supplementary motor area (SMA, BA6) and the superior temporal gyrus (STG, BA22). In fact, previous imaging studies have proposed that the SMG, the pars triangularis and the SMA are part of Baddeley's phonological loop (Baddeley, 1986) linking IFG activity to articulatory rehearsal and SMG activity to phonological storage (Demonet et al., 1994; Gold & Buckner, 2002; Paulesu et al., 1993; Tan et al., 2005).

Further support for an involvement of these areas in phonological processing is provided by a number of studies (e.g., Fiebach et al., 2002; Mechelli et al., 2007; Rumsey et al., 1997; Carreiras, Mechelli, & Price, 2006; Carreiras et al., 2007; Owen et al., 2004; Posner & Raichle, 1994; Ischebeck et al., 2004; Dietz et al., 2005, Borowsky et al., 2006) and also from imaging studies using pseudohomophones in visual word recognition reporting left and right inferior frontal gyrus activity (pars opercularis and triangularis) for pseudohomophones when compared to pseudowords (e.g., Edwards et al., 2005; Kronbichler et al., 2007).

Furthermore, bilateral insula activity seems to be involved in grapheme-phoneme conversion in visual word recognition (e.g., Fiebach et al., 2002; Fiez et al., 1998) as well as in phonological lexical access (e.g., Borowsky et al., 2006). Borowsky et al. (2006) reported posterior insula activity for exception words and anterior insula activity for pseudohomophones in a naming task. They proposed that the anterior and posterior insula reflect different levels of processing. Exception words should be read by lexical memory and pseudohomophones should be read by sublexical grapheme-phoneme conversion. Therefore, they concluded that the insula is sensitive to both sublexical and lexical processing.

These findings suggest that activity in these regions is related to phonological processing. This holds also for bilateral STG activation (e.g., Booth et al., 2002a; Tan et al., 2005). Activity in the STG was reported in response to individual speech sounds and letters (van Atteveldt et al., 2004) and to written and spoken narratives (Spitsyna et al., 2005) suggesting heteromodal processing and an involvement of the STG in cross-modal integration and multisensory convergence. Booth et al. (2002a) also reported heteromodal STG activity for spoken words and visual rhyming. Thus, the STG is supposed to process auditory and visual information and to be the site where auditory and visual pathways converge enabling automatic reciprocal processing of spoken and written language (Dijkstra et al., 1993).

There is also reasonable evidence that STG activity reflects processing of phonological and semantic information (e.g., Mesulam, 1990) and that the STG probably hosts the phonological word form lexicon, which is obviously involved in phonological lexical access. Thus, the STG could be the site where phonologically mediated lexical access takes place (e.g., Rumsey et al., 1997; Price et al., 1994; Wagner & Torgesen, 1987; Graves et al., 2007; Booth et al., 2002a,b). Therefore, we propose that the activity in the fronto-temporal area including the STG, as revealed by the contrast of pseudohomophones and spelling controls, reflects access to whole word phonological and probably semantic representations in the case of pseudohomophones.

Results from silent reading and visual lexical decision tasks further suggest that AG and SMG activity reflects lexical access. Joubert et al. (2004) compared silent reading of high frequency words assumed to index lexical processing and low frequency words and nonwords assumed to index sublexical processing. They found activation at the border of SMG and AG for silent reading of high frequency words and left inferior prefrontal gyrus activation for low frequency words and nonwords. They proposed that SMG/AG comprise the visual orthographic lexicon and that activation in this region reflects the mapping of orthographic whole word representations onto phonological whole word representations. Consistent with this view, Binder et al. (2003) reported AG and SMG activity to be higher for words than to word-like nonwords in a visual lexical decision task and attributed this activity to reflect semantic access.

Also Hofmann et al. (2008) reported left angular and supramarginal gyrus activity in visual lexical decision to words and nonwords using functional near infrared spectroscopy (fNIRS) and attributed this activity to reflect the connection of orthographic, phonological and semantic representations. Finally, Kronbichler et al. (2007) reported higher AG activity to pseudohomophones compared to pseudowords in a visual phonological decision task. These findings add further support to the idea that AG/SMG activity is involved in whole-word processing and furthermore that pseudohomophones probably activate their phonologically identical base words and thus signal lexical access.

Concerning the proposed conflict in the processing of pseudohomophones, we believe that the reported activity is not due to conflict monitoring or response conflict reported in the conflict literature. Response conflict or conflict monitoring is mostly linked to activity in the prefrontal cortex comprising the supplementary motor area (SMA, BA6) the anterior cingulate cortex (ACC, BA24) and the cingulate cortex (CC, BA32; e.g., Smith & Jonides, 1999; Botvinick et al., 2004, Ridderinkhof et al., 2004; Yeung et al., 2004). We suggested that processing of pseudohomophones is more demanding than processing of spelling controls because of conflicting information in the phonological and orthographic lexicon. Therefore, pseudohomophones should produce higher activity in regions believed to process this information and/or in regions that are known to reflect conflict processing. The results of the current study should therefore provide an answer to the locus of this kind of conflict processing if it is located at a lexical or at an extra-lexical level or both. Recently Fiebach et al. (2007) reported anterior cingulate cortex activity in a study on neighbourhood effects in visual word recognition. They proposed that ACC activity signals involvement of a domain-general, extra-lexical process and to play an important role for executive control functions during visual word recognition.

Prefrontal cortex activity for pseudohomophones and spelling controls was also obtained in the current study but this activity was cancelled out in the contrast of pseudohomophones and spelling controls, suggesting that activity in this area reflects a kind of processing which is present for both item groups. We therefore think that the current results cannot be explained by response conflict. Rather we propose that the P150 is too early to be related to decision processes and more likely to reflect an interaction of structural and lexico-semantic processes (e.g., Hauk et al., 2006b).

Activity in the fronto-temporal region comprising the inferior frontal gyrus is known to be active in silent reading and also in naming (e.g., Mechelli et al., 2007; Owen et al., 2004; Fiez & Petersen 1998; Rumsey et al., 1997; Price et al., 1994) which also speaks against response conflict as the basis for the reported results (but see Bunge et al., 2002; Garavan et al., 1999; Aron et al., 2004 for inferior frontal gyrus involvement in conflict processing independent of lexical processing). Mechelli et al. (2007) reported insula activity to be sensitive to the phonological relationship between stimuli in a primed word reading and picture naming task and concluded that phonologically related pairs require the discrimination between similar competing codes.

In support of this interpretation is a study by Bitan et al. (2007) who showed that children engage in automatic orthographic and phonological processing regardless of task requirements. Bitan et al. manipulated orthographic and phonological similarity between visually presented word pairs and compared conflicting and non-conflicting conditions in spelling and rhyme judgments. They found higher activity for the conflicting orthographic condition in bilateral inferior/superior parietal lobule (SPL) and higher activity for the conflicting phonological condition in the bilateral inferior frontal gyrus which is in areas which are close to those reported in the present study. This activity in the conflicting conditions are assumed to reflect repetitive mapping between orthography and phonology, and that increased phonological segmentation and covert articulation is necessary to verify the accuracy of the outcome. Bitan et al. proposed competition at two stages when readers encounter conflict between orthographic and phonological information. The first stage is early and comprises the generation or access to a representation; the second is later and comprises processes of response selection, which are assumed to be reflected in the obtained activity in the anterior cingulate/medial frontal cortex. Therefore, we propose that our findings indicate that activity in the left temporo-parietal region, comprising the SMG, and in the right fronto-temporal region, comprising the inferior frontal gyrus, the insula and the superior temporal gyrus, probably reflect lexical rather than extra-lexical processing. Pseudohomophones in contrast to spelling controls activate whole word phonological representations of their underlying base words.

The results of the current study showed that orthographic and phonological information interact at early stages of processing. This interaction is probably associated with the activation in left temporo-parietal (SMG) and right fronto-temporal regions (STG, IFG and insula) as revealed by the source analysis. This activation in the left temporo-parietal and the right fronto-temporal area is in line with previous research and further supports the hypothesis that an early mapping between orthography and phonology is an integral part of lexical access. In conclusion, our results (RTs, ERPs and LORETA) demonstrate rapid phonological activation in silent reading and thus provide evidence for the phonological mediation hypothesis and the claim that phonological processes are involved in lexical access in visual word recognition.

`Study 3`

Phonology Mediates Lexical Access in Visual Word Recognition[1]

Mario Braun, Florian Hutzler, Thomas F. Münte, Michael Rotte,

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Abstract

Phonological processing is one of the major research issues in visual word recognition. Of special interest is the question to what extent the process of phonological recoding guides lexical access. We addressed this issue by investigating pseudohomophone and baseword frequency effects in lexical decisions with event-related functional magnetic resonance imaging (fMRI). The fMRI analysis revealed activation in a network consistent with previous findings in visual word recognition. Inferior and middle frontal gyrus, insula, anterior cingulate cortex, inferior, and middle temporal gyrus including the left fusiform gyrus, as well as angular and supramarginal gyrus showed greater activation in response to pseudohomophones compared to pseudowords. The baseword frequency effect revealed greater activation for pseudohomophones derived from low than from high frequency basewords in the inferior frontal gyrus and insula in both hemispheres as well as in the anterior cingulate cortex. We propose that processing of pseudohomophones involves phonological activation at a lexico-semantic level and conclude that phonological recoding is an active process in visual word recognition.

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[1] Under Review in the Journal of Cognitive Neuroscience

Introduction

Reading requires the concerted action of orthographic, phonological, syntactic and semantic processes. Concerning the role of phonology most researchers agree that it takes place in both, spoken and written language processing. In reading aloud phonological processing is a necessary condition, since the orthographic code has to be translated into its phonological counterpart. Whether such phonological recoding is also active in silent reading is still a matter of debate (e.g., Van Orden, 1987; Perfetti & Bell, 1991; Seidenberg, 1985). Specifically, the question is, whether or to what extent phonological processing in silent reading aids lexical access.

Direct Access vs. Phonological Mediation

Two main hypotheses concerning this issue compete with each other: the hypothesis of direct access and the hypothesis of phonological mediation. The former states that there is a direct pathway from orthography to meaning (e.g., Seidenberg, 1985), and if phonological processing is performed in silent reading it is assumed to be post-lexical (i.e., after meaning is accessed). In contrast, the phonological mediation hypothesis (e.g., Van Orden, 1987; Tan & Perfetti, 1999) claims that phonological activation is a necessary condition for lexical access. Accordingly, phonology is assumed to be activated automatically prior to the access to word meaning and thus takes place relatively early during visual word recognition (for reviews see Berent & Perfetti, 1995; Frost, 1998; Van Orden, Pennington & Stone, 1990). The demonstration of phonological effects in a task that does not necessarily require phonology would contribute to the solution of this controversy as it points to the universality of phonological processing in visual word recognition. Empirical support for the direct access hypothesis can be provided by phonological interference effects.

Pseudohomophone Effect

The most prominent phonological interference effect is the pseudo-homophone effect (PHE) first described by Rubenstein, Lewis and Rubenstein (1971). These authors presented pseudohomophones (e.g., FEAL), that shared phonology but not orthography with real words (e.g., FEEL), and compared the responses to those for pseudowords (e.g., FEEP) differing in phonology as well as in orthography from real words. Using the lexical decision task they found longer response times and more errors for rejecting pseudohomophones than pseudowords. The PHE has been used as a marker for phonological activation in reading development (Goswami et al., 2001) and provides major constraints for computational models of visual word recognition (see Jacobs & Grainger, 1994; Seidenberg et al., 1996; Ziegler & Jacobs, 1995; Ziegler, Jacobs & Klüppel, 2001). Martin (1982) argued that the PHE can be explained in terms of an orthographic similarity confound, but subsequent research showed that this is not the case (e.g., Rastle & Brysbaert, 2006; Ziegler et al., 2001).

The standard explanation for the PHE is that a given pseudo-homophone contacts the lexical entry of its phonologically identical baseword in the lexicon, which in turn activates semantic information associated with that representation. Thus, the phonological lexicon and potentially co-activated semantics of the baseword signal the presence of a word, whereas the orthographic lexicon signals the absence. In lexical decision, it is assumed that resolving this conflict takes time and therefore participants show longer response times in rejecting pseudohomophones than pseudowords (Jacobs et al., 1998; Ziegler et al., 2001).

Baseword Frequency Effects

Furthermore, response time differences for pseudohomophones derived from high compared to those from low frequency basewords were observed in naming and lexical decision tasks. These baseword frequency effects (BFEs) are interpreted to reflect the activation of frequency sensitive word representations in a hypothetical mental lexicon (e.g., Forster & Chambers, 1973), which can be taken as further evidence for phonology-driven lexical access.

BFEs are most often investigated in studies using the naming task (e.g., Reynolds & Besner, 2005), but also in semantic categorization and proofreading (Ziegler, Van Orden & Jacobs, 1997), as well as in the phonological decision task (Grainger, Spinelli & Ferrand, 2000; Taft & Russel, 1992; McCann et al., 1988). However, evidence is mixed, since some researchers reported effects (e.g., Taft & Russel, 1992; Borowsky & Masson, 1999), whereas others did not (e.g., Seidenberg et al., 1996; McCann & Besner, 1987;

McCann, Besner & Davelaar, 1988; Grainger, Spinelli & Ferrand, 2000; Herdmann, LeFevre & Greenham, 1996). Similarly, baseword frequency effects in silent reading were sometimes reported in lexical decision (Van Orden, 1991; Ziegler et al., 2001) and sometimes not (McCann et al., 1988; Seidenberg et al., 1996).

Models of Visual Word Recognition

Current models of visual word recognition, like the dual-route cascaded model (DRC; Coltheart et al., 2001) or the multiple read-out model including phonology (MROM-P; Jacobs et al., 1998) predict and successfully simulate the PHE in lexical decision. Both models explain the pseudo-homophone disadvantage in terms of higher summed global lexical activation in an implemented phonological lexicon which prolongs a temporal deadline mechanism for generating no-responses.

The DRC and the MROM-P also make the same predictions concerning the BFE. Both models feature frequency-based representations and predict that pseudohomophones derived from low frequency basewords lead to faster rejections than pseudohomophones from high frequency basewords. This is proposed, because pseudohomophones from low frequency words should produce little activation in the phonological lexicon and therefore the conflict between orthographic and phonological information should be low. In contrast, activation in the phonological lexicon should be greater for pseudohomophones derived from high frequency basewords, leading to strong 'word present' signals which would result in more errors and longer response times in lexical decision.

However, the empirical findings for the BFE in lexical decision are at odds with the predictions of both the DRC and MROM-P: pseudohomophones derived from high frequency basewords are rejected faster than those from low frequency basewords (e.g., Ziegler et al., 2001; Van Orden, 1991). In the light of this counterevidence a spelling-verification mechanism was proposed to account for this reversed BFE (e.g., Becker, 1976; Paap et al., 1987; Paap et al., 1982). The idea is that pseudohomophones activate high frequency basewords faster, because these have higher resting levels and are well represented in the orthographic lexicon. Thus, spelling verification is faster for pseudohomophones from high compared to those from low frequency basewords (see Ziegler et al., 2001, for further evidence of a spelling-verification mechanism).

Brain Activation

Previous neuroimaging research identified two main reading circuits, a dorsal occipito-parietal-frontal and a ventral occipito-temporal circuit. The dorsal circuit is believed to include the angular and supramarginal gyri, the inferior parietal lobule and the posterior superior temporal gyrus including Wernicke's Area (e.g., Dejerine, 1891; Damasio & Damasio, 1983; Henderson, 1986) as well as the left inferior frontal gyrus comprising pars opercularis and triangularis (e.g., Pugh et al., 2000; Paulesu, Frith & Frackowiak, 1993). It is assumed to serve the mapping of orthographic to phonological representations with a pronounced processing of phonological information (e.g., Rumsey et al., 1997). The ventral circuit consists of lateral extrastriate areas, the inferior and middle temporal gyri including the fusiform gyrus and is supposed to process mainly orthographic information (e.g., Henderson, 1986; Fiez & Petersen, 1998; Nobre, Allison, & McCarthy, 1994; Rumsey et al., 1997, Cohen et al., 2000; Cohen & Dehaene, 2004; Cohen et al., 2008; Vinckier et al., 2007).

Phonology

Brain areas involved in phonological processing in silent reading comprise the inferior frontal gyrus (Fiebach et al., 2002; Ischebeck et al, 2004), the bilateral insula (Mechelli et al., 2007; Borowsky et al., 2006), the superior temporal gyrus (Booth et al., 2002; Mesulam, 1990; Rumsey et al., 1997; Price et al., 1994), the supramarginal and angular gyrus (Joubert et al., 2004; Binder et al., 2003; Paulesu, Frith, & Frackowiak, 1993; Kronbichler et al., 2007; Ischebeck et al., 2004; Law et al., 1991; Church et al., 2008), and the supplementary motor area (Hagoort et al., 1999; Carreiras, Mechelli & Price, 2006; Price et al., 1994). Concerning the functional role of the left inferior frontal gyrus and the insula, activation has been proposed to indicate grapheme-phoneme conversion and/or processing for lexico-semantic access (e.g., Fiebach et al., 2002; Heim et al., 2005; Poldrack et al., 1999).

Conflict

Furthermore, pre-frontal cortex activation in the supplementary motor area and the anterior cingulate cortex is often reported in studies of visual word recognition involving conflict processing (e.g., Petersen et al., 1988; Awh et al., 1996). Anterior cingulate cortex activation is observed when orthographic or phonological decisions are required (e.g., Rumsey et al., 1997; Booth et al., 2002; Fiebach et al., 2007; Binder et al., 2003; Carreiras et al., 2006) and is considered to reflect cognitive or executive control processes. Nevertheless, its exact nature is still under discussion since it is also active in reading aloud (e.g., Fiez & Petersen, 1998). Supplementary motor area activation is believed to reflect rehearsal and silent articulation processes (e.g., Price et al., 1994; Paulesu et al., 1993; Wise et al., 1991; Demonet et al., 1992).

The Present Study

The aim of the present fMRI study was to provide neuroimaging evidence of phonological processing in visual word recognition by examining the PHE in lexical decision. Paralleling the logic used in behavioural studies, brain activations should be modulated by the pseudo-homophone – pseudo-word contrast. In addition, if phonological processing constrains lexical access at a whole-word level, neural activation in response to pseudohomophones should be influenced by baseword frequency. In particular, BFEs would provide evidence for phonology-driven lexical access to frequency-sensitive representations and therefore support models of visual word recognition implementing whole-word phonological as well as frequency-sensitive representations.

We assume that lexical decisions to pseudohomophones are in general more difficult than decisions to pseudowords. This is probably due to the conflict introduced in the hypothetical mental lexicons: the phonological lexicon would signal the presence, of a word whereas the orthographic lexicon would signal its absence. This should result in greater activation in regions hosting these lexicons and/or in regions involved in conflict processing such as the medial pre-frontal cortex. Therefore, the results of the present study should provide evidence about the likely loci of phonological processing in visual word recognition.

With regard to the BFE, we assume that lexical decisions to pseudohomophones derived from low frequency basewords are more difficult due to lower resting levels of their orthographic representations (Grainger & Jacobs, 1996). Those should produce greater activation in regions involved in lexical access, but probably also in regions sensitive to conflict processing. Furthermore, if spelling-verification is an active process in lexical decisions to pseudohomophones we expect effects in brain regions associated with orthographic processing.

Material and Methods

Participants

Fourteen right-handed students (three men, mean age 23 years) from the University of Magdeburg participated in the study. All participants were native German speakers, had normal or corrected to normal vision, were free of any current or past neuropsychiatric disorders and did not take psychoactive medication. Data from all participants were used in the analyses. Participants were compensated for their time with 24 €.

Stimuli

The critical stimulus set contained 480 stimuli (240 words and 240 nonwords). Of the 240 word stimuli 120 served as fillers. Of the 240 nonwords half were pseudohomophones and half were pseudowords. Pseudohomophones and pseudowords were derived from the same basewords by replacement of one letter. Where possible the letter was changed at the same position such that a vowel was replaced by another vowel and a consonant by another consonant. Pseudohomophones had the same phonology, but differed in spelling from their basewords. Pseudowords differed in spelling and also in phonology from their basewords. 'SAHL' is a pseudo-homophone derived from the baseword 'SAAL' (room) and 'SARL' is the corresponding pseudo-word. Of the pseudohomophones and the pseudowords one third had three, one third had four and one third had five letters. Half of the pseudohomophones and pseudowords of each length were derived from high frequency basewords (more than 20 occurrences per million, mean 820.5). The other half of the pseudohomophones and pseudowords had low frequency basewords (less than 20 occurrences per million, mean 5.9). Frequency estimates were taken from the CELEX database (Baayen et al., 1995). To rule out orthographic similarity as a potential source of the PHE, pseudohomophones and pseudowords were matched according to the strong criteria put forward by Martin (1982), controlling for bigram frequency (type and token counts) and number of orthographic neighbours (N). Table 1 shows the matched variables for pseudohomophones, pseudowords and words. Table 2 gives sample stimuli. Of the 120 word stimuli, one third had three, one third had four, and one third had five letters. Half of the word stimuli of each word length were of high frequency (more than 11 occurrences per million, mean 1405.6) and the other half were of low frequency (less than 11 occurrences per million, mean 3.9). The word stimuli were matched on bigram frequency (type count), number of syllables (Syl), number of neighbours (N), summed frequency of neighbours (FN) and number of higher frequency neighbours (HFN).

Table 1. Matched variables for pseudohomophones, pseudowords and words

	Frequency		
	low	high	mean
	pseudohomophones		
BF (type)	32	42	37
BF (token)	2699	3633	3166
N	3.4	3.5	3.5
	pseudowords		
BF (type)	32	42	37
BF (token)	4857	8440	6649
N	3.4	3.6	3.5
	words		
BF (type)	47	57	52
FN	188944	39777	114360
HFN	1.9	0.8	1.4
N	3.3	4.3	3.8
Syl	1.5	1.3	1.4

Note. BF (type) = summed positional bigram count; BF (token) = summed positional bigram frequency count; N = number of neighbours; FN = summed frequency of orthographic neighbours; HFN = number of higher frequency orthographic neighbours; Syl = number of syllables.

Table 2. Sample stimuli

	pseudohomophones		pseudowords		basewords	
Length	low	high	low	high	low	high
3-letters	AXD	ALD	AXG	ALZ	AXT	ALT
4-letters	EKKE	FOLK	EFKE	BOLK	ECKE	VOLK
5-letters	DURSD	RAICH	DURSG	REUCH	DURST	REICH

Procedure and Tasks

Participants were placed in the scanner and were given written instructions. They were told that they would see letter strings, some of which were German words and some were nonwords. Participants were instructed to indicate via button press as rapidly as possible, but not to the expense of accuracy whether the stimulus was a German word or not. Two magnet-compatible response boxes (one in each hand) were used. The response hands were counterbalanced across participants. They performed 15 practice trials to familiarize them with the task. The experiment was divided into three runs. The experimental trials were presented in randomized order for each participant. Each trial began with a 1000 msec presentation of a fixation mark in the centre of the screen. The fixation mark (+) was replaced by the stimulus, which remained on the screen for another 1000 msec and required the button press response. Responses with reaction times below 200 msec and above 2000 msec were excluded (0.39%). The stimuli were displayed in yellow on a grey background using upper case letters set in Courier 48pt font. Visual images were back-projected onto a screen by a LED-projector and participants viewed the images through a mirror on the head coil. The whole experiment took about 40 minutes. The experiment was programmed and ran using Presentation experimental software (Neurobehavioral Systems Inc, Albany, CA).

Image Acquisition

Functional and structural imaging was performed with a General Electric 1.5 Tesla Signa scanner (General Electric, Fairfield, CT, USA) using a standard head-coil. Conventional high-resolution structural images (rf-spoiled GRASS sequence, 60 slice sagittal, 2.8 mm thickness) were followed by functional images sensitive to blood oxygenation level-dependent contrast (echo planar T_2*-weighted gradient echo sequence, TR/TE/flip angle =2000 msec/40 msec/90°, 34 slices). Low frequency noise was removed with a high-pass filter (128s). Data were analysed using the general linear model in SPM2 (Statistical Parametric Mapping; Wellcome Department of Cognitive Neurology, London, UK: http://www.fil.ion.ucl.ac.uk/spm). The first three scans of each run were discarded to avoid magnetic saturation effects. Firstly, data were pre-processed for each subject: after separate realignment procedure for the three runs, a co-registration step was performed to adjust the images of each part to the first run of individual subjects. The complete dataset was then spatially normalized to the Montreal Neurological Institute template with interpolation to 3 x 3 x 3 mm space.

Statistical fMRI Analysis

After fixed effect analysis separately performed for each subject, these contrast images were grouped by paired t-tests in a random effects analysis based on the effect of interest. The basis of this analysis represents the voxel by voxel comparison of effects (statistical results based on FDR corrected values at threshold of $p < .05/.02$). Stereotaxic coordinates for voxels with maximal z-values within activation clusters are reported in the MNI coordinate system. The MNI-Space Utility (Sergey Pakhomov: http://www.ihb.spb.ru/~pet_lab/MSU/MSUMain.html) was used to label MNI coordinates in terms of Talairach daemon anatomical region labels. Converting MNI coordinates to Talairach coordinates is performed according to a nonlinear transformations approach, as described at the CBU Imaging web site.

Results

Behavioural Results

Response times to words were about 150 msec faster than to nonwords. Error rates to words and nonwords were virtually identical (2.99% vs. 3.08%). Words were responded to fastest followed by responses to pseudowords and pseudohomophones. Response times were slower to low than to high frequency items in each category. Table 3 shows the means of response times and error rates for the different stimuli conditions. For response times, separate 2 x 2 ANOVAs with phonology (pseudohomophones vs. pseudowords) and baseword frequency (high vs. low) as factors were performed for participants (F1) and items (F2). In the repeated measure ANOVA by participants the factors phonology and baseword frequency were treated as within-subject factors. The analyses revealed effects of phonology [$F1(1,13) = 25.32$, $p < .001$, $MSE = 22600$; $F2(1,236) = 11.55$, $p < .001$, $MSE = 104572$] and of baseword frequency [$F1(1,13) = 7.49$, $p = .017$, $MSE = 12154$; $F2(1,236) = 4.69$, $p = .031$, $MSE = 42446$], and also a significant interaction [$F1(1,13) = 11.47$, $p = .004$, $MSE = 7661$; $F2(1,236) = 3.89$, $p = .049$, $MSE = 35219$]. Response times were slower to pseudohomophones derived from low than from high frequency basewords. In contrast, response times to pseudowords did not differ with regard to baseword frequency. Thus, phonology and baseword frequency reliably modulated response times for pseudohomophones, but not for spelling pseudowords.

Table 3. Response time means and error rates for pseudohomophones, pseudowords and words.

	Response Time (msec)		Error rates (%)	
	(baseword) Frequency		(baseword) Frequency	
	low	high	low	high
PH	954	901	1.71	0.67
PW	891	884	0.40	0.30
WO	779	737	1.23	1.66

Note. PH = pseudohomophones, PW = pseudowords and WO = words

Imaging Results

Pseudohomophone Effect

No brain region showed greater activation for pseudowords compared to pseudohomophones. Brain activation to pseudohomophones contrasted with pseudowords was greatest in the right hemisphere comprising the inferior-orbito-frontal gyrus as well as the insula and the superior temporal gyrus. Furthermore, left and right supplementary motor area and anterior cingulate cortex as well as left pars orbitalis and left insula, left occipito-temporal gyrus including the fusiform gyrus, right inferior-temporal and middle-temporal gyrus and left and right middle frontal gyrus showed greater activation for pseudohomophones. The result held also for activation in the left inferior parietal lobule and left supramarginal gyrus (see Figure 1 and Table 4).

Table 4. Brain regions exhibiting reliably stronger activation for pseudohomophones than for pseudowords.

Brain Region	Brodmann Area	hem	x	y	z	mm^3	Zmax
pseudohomophones > pseudowords							
Insula, inferior, middle frontal gyrus - pars opercularis, triangularis, orbitalis	11,13,38,44-47	R	45	39	-18	531	4.90
			36	24	-15		4.87
			45	30	-16		4.59
Superior, medial frontal gyrus, anterior cingulate gyrus	6,8,9,32	L/R/C	0	30	45	576	4.32
			-6	15	60		4.10
			9	15	54		3.73
Insula, inferior frontal gyrus - pars orbitalis	47,13	L	-30	24	-15	151	4.2
Inferior, middle temporal gyrus	20	R	54	-42	-15	40	4.06
Inferior, middle temporal gyrus, fusiform gyrus	20,21,37	L	-60	-48	-15	83	3.71
			-51	-33	-12		3.45
			-51	-54	-21		3.26
Middle frontal gyrus	8,9,46	R	51	18	36	30	3.33
Middle frontal gyrus	8,9,46	L	-39	42	-15	26	3.30
Inferior parietal lobule, supramarginal gyrus	7,40	L	-39	-69	45	7	3.11

Note. x, y, z = coordinates according to MNI stereotactic space, cluster size in voxels, $p < 0.05$ (FDR corrected), values in grey represent coordinates of co-activated cluster-centres showing also significant differences between conditions.

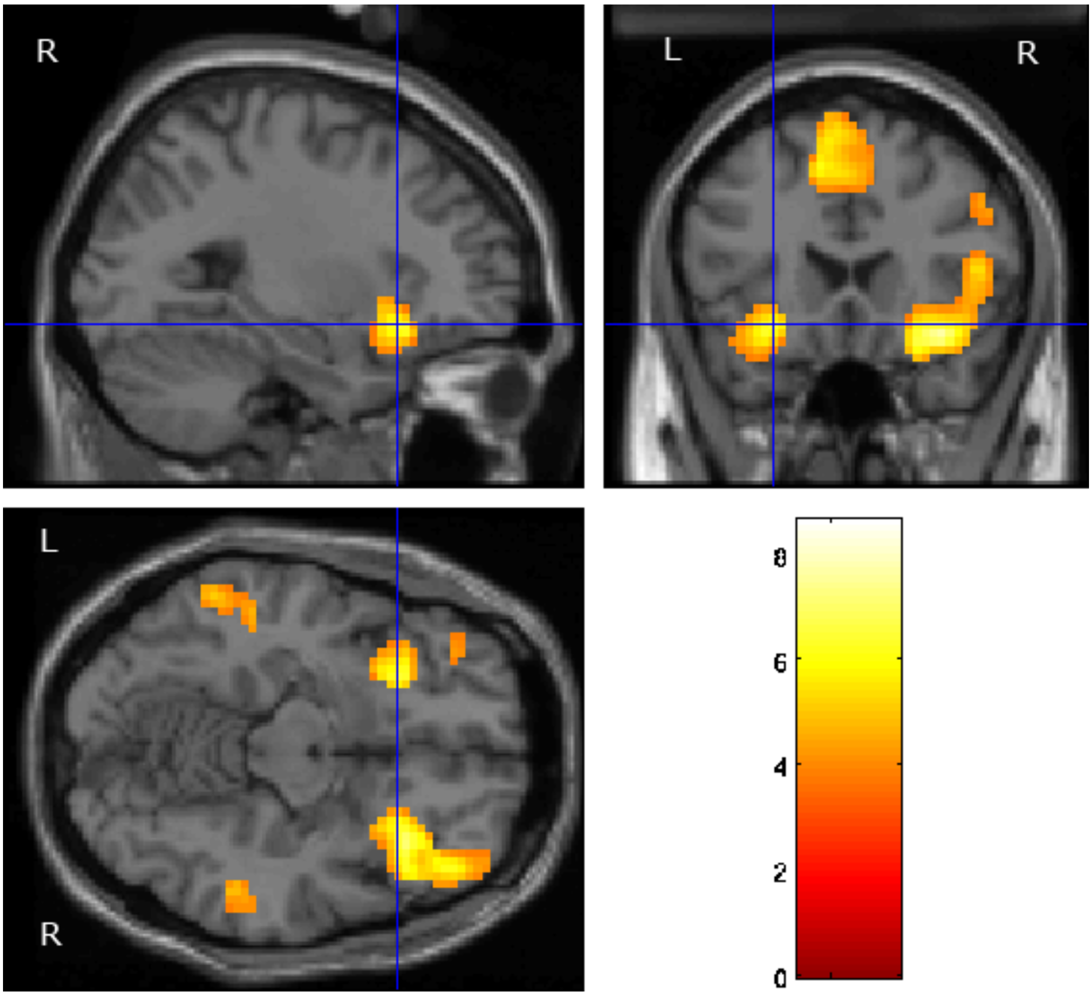

Figure 1. Brain regions exhibiting greater activation for the processing of pseudohomophones compared to pseudowords: right SFG, insula, STG, IFG, MFG (peak at 45 39 -18, BA 11,13,38,44-47); left insula, IFG (peak at -30 24 -15, BA13,47); left/right SMA, ACC (peak at 0 30 45, BA 6,8,9,32); right ITG, MTG (peak at 54 -42 -15, BA 20); left ITG, MTG, FG (peak at -60 -48 -15, BA 20,21,37); left/right MFG (peak at -39 42 -15/51 18 36, BA 8,9,46); left IPL/SMG (peak at -39 -69 45, BA 7,40). Colour bar indicates T values. L = left, R = right.

Note: BA = Brodmann Area, SFG = superior frontal gyrus, STG = superior temporal gyrus, IFG = inferior frontal gyrus, MFG = medial frontal gyrus, SMA = supplementary motor area, ACC = anterior cingulate cortex, ITG = inferior temporal gyrus, MTG = middle temporal gyrus, FG = fusiform gyrus, MFG = medial frontal gyrus, IPL = inferior parietal lobule, SMG = supramarginal gyrus.

Pseudohomophone Effect - low frequency basewords

To obtain a more detailed picture of the PHE, we calculated activation differences between pseudohomophones and pseudowords derived from low frequency basewords since those are reported to evoke the clearest pseudo-homophone effects (e.g., Ziegler et al., 2001). As Figure 2 and Table 5 show, pseudohomophones from low frequency basewords showed greater activation than pseudowords in extensive brain regions involved in language processing. The greatest difference in activation was found in pre-central and inferior medial and superior frontal regions including the supplementary motor area and the anterior cingulate cortex. Furthermore, bilateral inferior frontal gyrus and insula, superior temporal gyrus, left angular and supramarginal gyrus, inferior parietal lobule and the right supramarginal gyrus were more activated for pseudohomophones than pseudowords. Furthermore, left inferior temporal areas including the fusiform gyrus and right temporal gyrus showed greater activation for pseudohomophones compared to pseudowords derived from low frequency basewords (FDR corrected, $p < .02$; see Figure 2 and Table 5). Figure 3 shows the mean parameter estimates for the contrast of pseudohomophones and pseudowords.

Table 5. Brain regions exhibiting reliably stronger activation for pseudohomophones vs. pseudowords derived from low frequency basewords

Brain Region	Brodmann Area	hem	x	y	z	mm^3	Zmax
pseudohomophones > pseudowords							
Anterior cingulate, cingulate,	6,8,9,24,32	L/R/C	-3	24	42	1054	5.10
superior and medial frontal gyrus			3	33	39		4.98
			-9	15	60		4.77
Insula, superior temporal gyrus,	8-11,13,22,38,44-47	R	33	24	-18	983	5.02
precentral gyrus, inferior, middle			48	18	36		4.15
and superior frontal gyrus			48	24	-12		4.04
Insula, parahippocampal gyrus,	11,13,38,47	L	-24	15	-18	337	4.62
superior temporal gyrus, inferior,			-27	24	-12		4.47
middle frontal gyrus			-45	24	-21		3.24
Inferior, superior parietal lobule,	7,19,39,40	L	-24	-69	45	364	4.38
precuneus, superior temporal gyrus,			-39	-57	33		3.66
angular-, supramarginal gyrus			-51	-45	45		3.54
Inferior and middle frontal gyrus	10,11,44-47	L	-42	54	-6	157	3.91
			-48	36	6		3.85
Thalamus		L/R	0	-15	12	34	3.89
Inferior and superior parietal lobule	7,40	R	39	-60	51	73	3.86
			45	-51	54		3.59
Fusiform gyrus	37	L	-48	-60	-15	19	3.72

Note. x, y, z = coordinates according to MNI stereotactic space, cluster size in voxels, $p < 0.02$ (FDR corrected), values in grey represent coordinates of co-activated cluster-centres showing also significant differences between conditions.

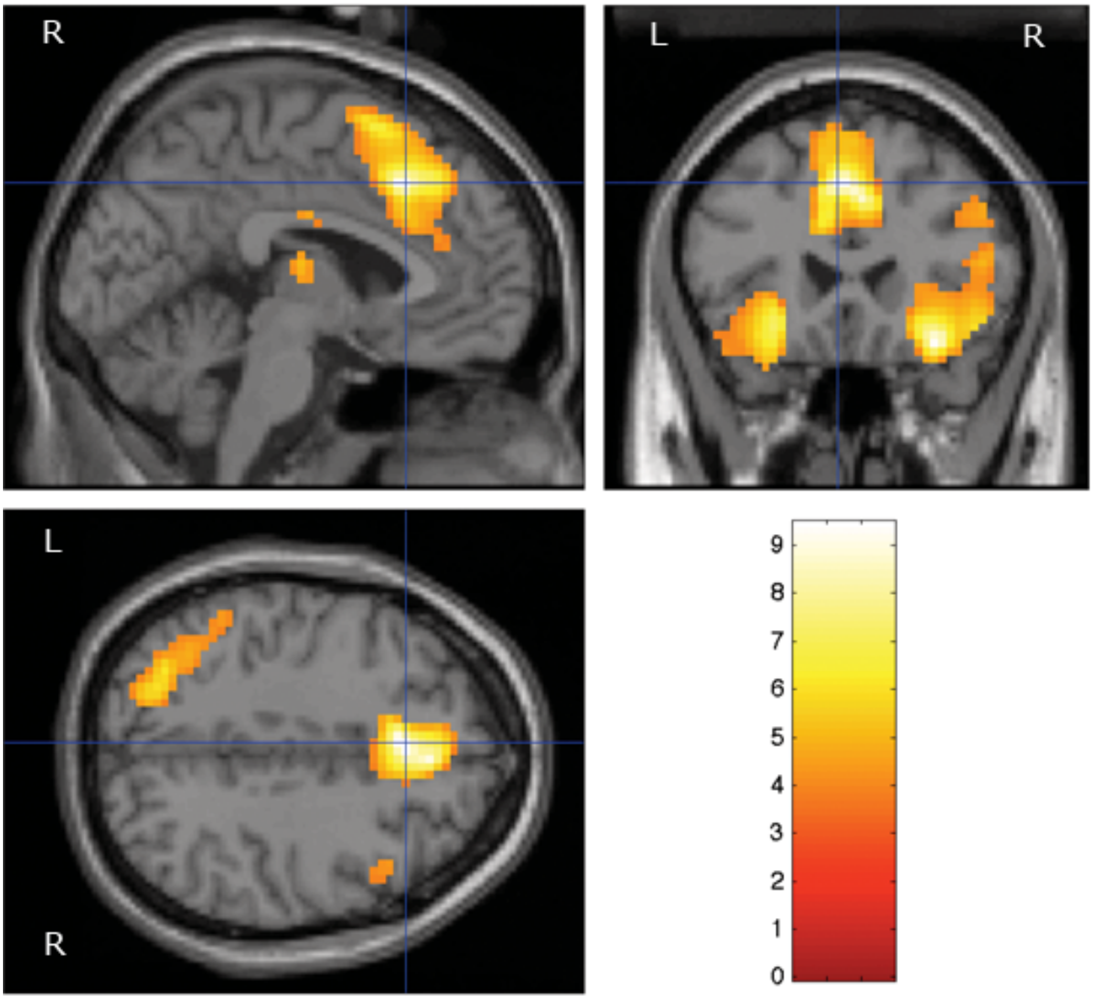

Figure 2. Brain regions exhibiting greater activation for the processing of pseudohomophones and pseudowords derived from low frequency basewords: SMA/ACC (peaks at -3 24 42; BA 6,8,9,24,32); right frontal, precentral gyrus, IFG, insula, STG (peak at 33 24 -18; BA 8-11,13,44-47,22,38); left frontal gyrus, insula, STG, IFG (peak at -24 15 -18; BA 11,13,38,47); left IPL, SPL, AG, SMG (peaks at -24 -69 45, BA 7,9,39,40), right IPL (39 -60 51, BA 7,40); left/right Thalamus (peak at 0 -15 12) and left FG (peak at -48 -60 -15, BA37). Colour bar indicates T values. L = left, R = right.

Note: BA = Brodmann Area, SMA = supplementary motor area, ACC = anterior cingulate cortex, IFG = inferior frontal gyrus, STG = superior temporal gyrus, IPL = inferior parietal lobule, SPL = superior parietal lobule, SMG = supramarginal gyrus, AG = angular gyrus, FG = fusiform gyrus.

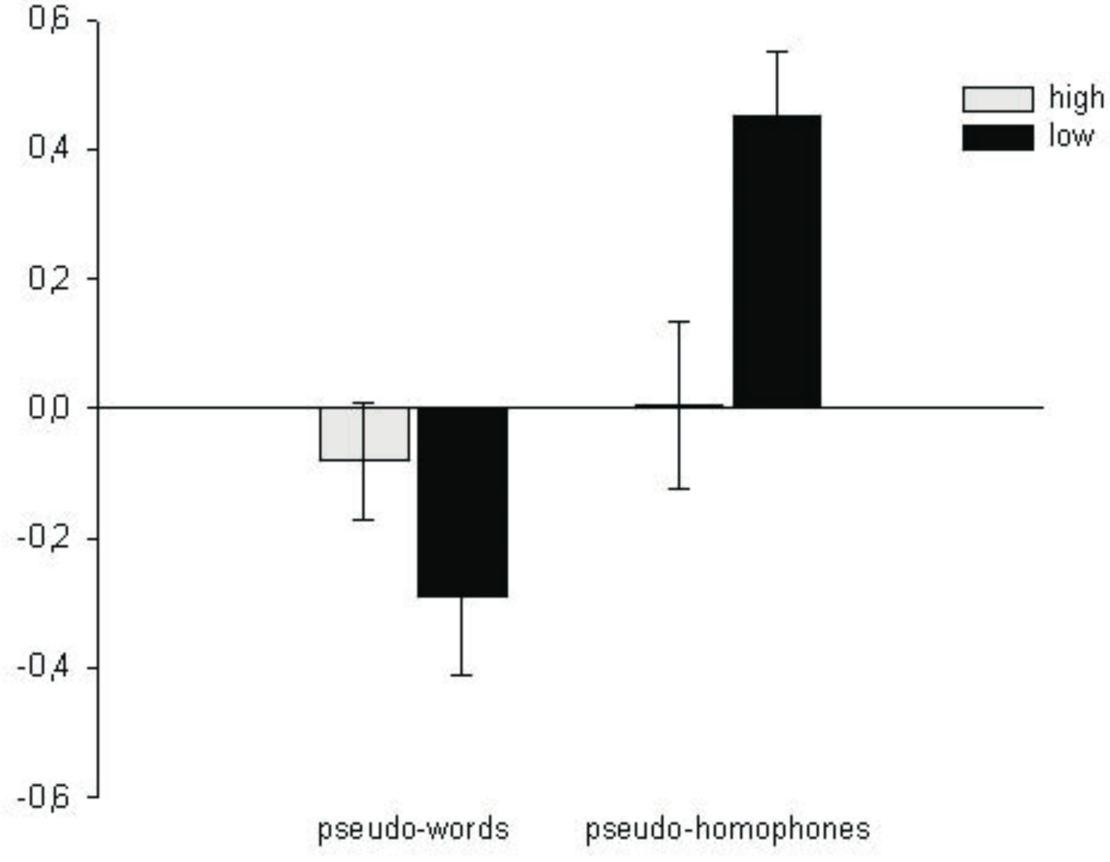

Figure 3. Mean parameter estimates for the comparison of pseudohomophones and pseudowords in the inferior frontal gyrus, anterior cingulate and the supplementary motor area. Graphs depict the strength of the signal as illustrated by the beta values that exhibit interaction between conditions. For each subject, beta values were extracted from a region of interest (ROI) based on the activated clusters from the second-level contrast, which showed greater activation for pseudohomophones in the BOLD signal compared to pseudowords: left/right IFG, insula (peaks at -24 15 -18/33 24 -18, BA 13,47); left/right SMA, ACC (peak at -3 24 42, BA 6,32). These clusters were combined with the structural definitions of the anatomical automatic label package (Tzourio-Mazoyer et al., 2002) for overlap. Beta values were averaged across the three runs and across all subjects to obtain a mean beta value for each event in each condition to show the main effect of phonology in the BOLD signal. ROI definition and beta value extraction were performed with the ROI toolbox Marsbar (Brett et al., 2002). Error bars represent standard error of the mean.

Note: BA = Brodmann Area, IFG = inferior frontal gyrus, SMA = supplementary motor area, ACC = anterior cingulate cortex.

Baseword Frequency Effect

No brain region showed activation differences for the contrast of pseudowords from low vs. high frequency basewords. In contrast, there was a baseword frequency effect for pseudohomophones. Activation was greater for pseudohomophones from low than from high frequency basewords in the left and right inferior frontal gyrus comprising pars orbitalis and bilateral insula. Additional pars triangularis activation was observed in the left hemisphere. Furthermore, a small portion of the anterior cingulate cortex showed greater activation for pseudohomophones form low frequency words (FDR corrected, p < .05). Figure 4 and Table 6 illustrate the brain regions revealing greater activation for pseudohomophones from low compared to those from high frequency basewords.

Table 6. Brain regions exhibiting reliably stronger activation for pseudohomophones derived from low vs. pseudohomophones derived from high frequency basewords.

Brain Region	Brodmann Area	hem	x	y	z	mm^3	Zmax
pseudohomophones (low) > pseudohomophones (high)							
Inferior frontal gyrus - pars orbitalis, insula	47,13	R	30	21	-12	36	4.21
Inferior frontal gyrus – pars orbitalis, pars triangularis, insula	47,45,13	L	-33	18	3	60	4.14
Anterior cingulate	32	L	-15	0	51	4	4.01
Anterior cingulate	32	R	9	21	36	1	3.81

Note. x, y, z = coordinates according to MNI stereotactic space, cluster size in voxels, p < 0.05 (FDR corrected)

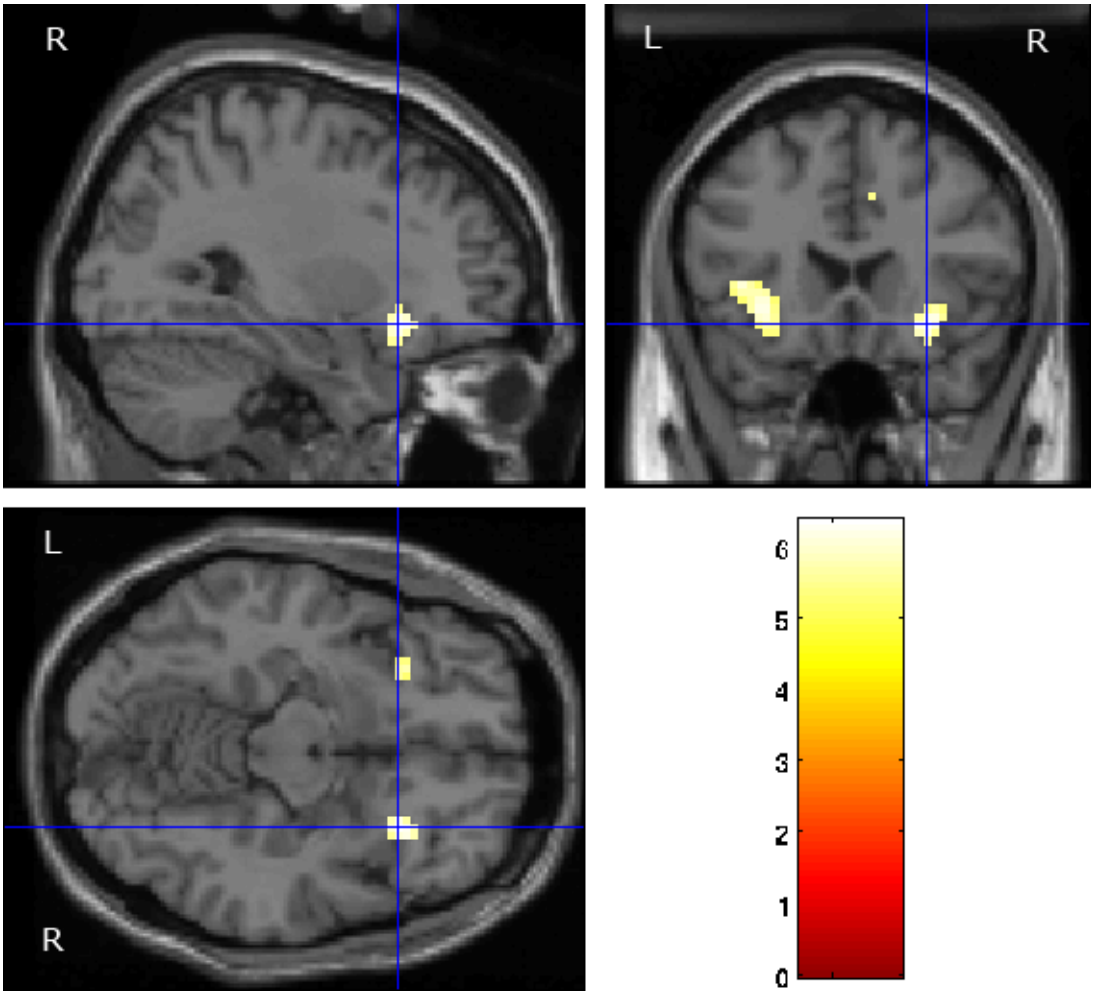

Figure 4. Brain regions exhibiting greater activation for pseudohomophones derived from low frequency basewords compared to pseudohomophones derived from high frequency basewords: right insula, IFG (peak at 30 21 -12, BA 13,47); left insula, IFG (peak at -33 18 -3, BA 13,45,47); ACC (peak at 9 21 36, BA 32). Colour bar indicates T values. L = left, R = right.

Note: BA = Brodmann Area, IFG = inferior frontal gyrus, ACC = anterior cingulate cortex.

Discussion

In the introduction, we outlined the empirical criteria for an involvement of phonological recoding in silent reading, i.e. the pseudo-homophone effect (differences in response time and brain activation between pseudohomophones and pseudowords derived from the same basewords) and the baseword frequency effect (differences in response time and brain activation for pseudohomophones derived from basewords of different lexical frequency). The current behavioural and neuroimaging results unequivocally demonstrate both effects and thus provide strong support for the phonological mediation hypothesis (e.g., Coltheart et al., 2001; Frost, 1998; Van Orden, 1987; Tan & Perfetti, 1999). To briefly reiterate the results, responses to pseudohomophones were 50 msec slower than those to pseudowords. The comparison of pseudohomophones and pseudowords of different baseword frequencies revealed that the PHE was strongest for pseudohomophones derived from low frequency basewords (63 msec). This was also confirmed for the BFE: pseudohomophones derived from low frequency basewords were responded to 53 msec slower compared to those derived from high frequency basewords. Thus, we replicated previously in behavioural studies reported PHEs and BFEs in the scanner.

Pseudohomophone Effect

In the hemodynamic response the PHE was evident in greater bilateral activation for pseudohomophones compared to pseudowords in frontal, inferior frontal, inferior, and middle temporal brain areas. These regions comprise the inferior frontal gyrus, the insula, the supplementary motor area, the anterior cingulate cortex, left inferior and middle temporal areas including the fusiform and the supramarginal gyri. The PHE for low frequency basewords revealed greater activation for pseudohomophones in nearly the same areas. Additional activation was found in pars opercularis and triangularis of the inferior frontal gyrus, in the angular gyrus and in Wernicke's area. These additional activations suggest a more prominent role of phonological processing for low frequency stimuli (Fiebach et al. 2002).

We propose that activation in the inferior frontal gyrus, insula, superior temporal, supramarginal, and angular gyrus signals phonology-driven lexico-semantic processing in response to pseudohomophones. Pseudohomophones differed in orthography but not in phonology from their basewords and elicited greater activation than pseudowords which differ in both, orthography and phonology from their basewords.

Activation in the inferior frontal gyrus is reported to be involved in visual word processing. Ischebeck et al. (2004) linked pars opercularis activation to grapheme-phoneme conversion (see also Rumsey et al., 1997; Joubert et al., 2004; Fiebach et al., 2002; Fiez et al., 1998; Paulesu, Frith, & Frackowiak, 1993) and Fiebach et al. (2002) proposed that pars triangularis activation signals lexico-semantic access involving processes of lexical search and lexical selection (see also Heim et al., 2005; Thompson-Schill et al., 1997). Furthermore, pars orbitalis activation was repeatedly involved in semantic processing (e.g., Mechelli et al., 2007; Nixon et al., 2004; Devlin, Matthews, & Rushworth, 2003; Gold, Balota, Kirchhoff, & Buckner, 2005, but see Snyder et al., 2007 for a cognitive control account of the left inferior pre-frontal cortex). Poldrack et al. (1999) proposed that activation in left pars opercularis and triangularis signals semantic processing and that more posterior/dorsal activation reflects phonological and semantic processing. They concluded that phonological processing is automatically engaged during semantic processing (see Fiez et al., 1997 for a similar framework of semantic and phonological processing).

Furthermore, left insula activation was recently associated with the discrimination of similar competing phonological and articulatory codes in reading aloud (e.g., Mechelli et al., 2007) which points to phonological word forms as possible agent for frequency effects in reading aloud. In line with other studies the present pseudohomophones activated pars orbitalis, pars opercularis and pars triangularis of the left inferior frontal gyrus as well as the insula (e.g., Owen et al., 2004; Rumsey et al.,1997; Edwards et al., 2005; Kronbichler et al., 2007; Borowsky et al., 2006; Simos et al., 2002).

Activation in the supplementary motor area and the anterior cingulate cortex is associated with phonological (e.g., Awh et al., 1996; Petersen et al., 1988; Carreiras et al., 2006) and also conflict processing (Smith & Jonides, 1999; Botvinick, Cohen & Carter, 2004; Ridderinkhof et al., 2004). Up to now it is not clear whether this activation reflects greater demands on phonological processing or is caused by general difficulty imposed by material and task demands.

Inferior and middle temporal areas comprising the fusiform gyrus are believed to be involved in pre-lexical abstract letter string recognition (e.g., Cohen et al., 2000; Cohen & Dehaene, 2004; Cohen et al., 2008; Vinckier et al., 2007). The middle portion of the fusiform gyrus is referred to as the "basal temporal language area" (Bookheimer et al., 1995) or as the "visual word form area" where perceptually invariant higher-order orthographic units are computed from the visual input. Recent findings also suggest a possible involvement in lexical processing. Kronbichler et al. (2007) reported activation differences in the fusiform gyrus by comparing words, pseudowords and pseudohomophones in a visual phonological decision task. Words elicited less activation compared to pseudohomophones and pseudowords, which did not differ in activation. Therefore, Kronbichler et al. suggested that the fusiform gyrus not only computes letter string representations, but probably is also the region where word-specific orthographic representations are stored. Visual input matching stored representations (i.e., words) leads to less activation compared to visual input that does not (e.g., pseudowords). The pseudohomophones of Kronbichler et al. differed in activation from pseudowords in the left inferior frontal gyrus, but in contrast to the present study, activation was found to be lower for pseudohomophones than for pseudowords which is likely due to the different tasks employed (phonological decision in Kronbichler et al. compared to lexical decision in the present study).

The temporal resolution of brain imaging data does not allow for a decision as to whether the observed differences in neural activation elicited by pseudohomophones and pseudowords in temporo-parietal and inferior frontal areas were due to initial phonological processing after early visual feature extraction or whether they were due to the modulation of these areas during later processing. Evidence for a strong coupling of inferior-occipito-temporal and inferior frontal areas was recently provided by Mechelli et al. (2005) who reported a functional differentiation of the fusiform gyrus for words and pseudowords in silent reading. Using statistical parametric mapping and dynamic causal modelling to investigate the process of translating orthography to phonology they found a strong coupling of activation in the fusiform gyrus and the inferior frontal gyrus. Mechelli et al. identified a ventral inferior frontal (pars triangularis) and an anterior fusiform system more engaged by lexico-semantic processing, as exception words elicited greater activation than pseudowords. A second system, comprising a left pre-central and a more posterior fusiform area was more active for pseudowords and was interpreted to reflect direct retrieval of phonology from orthography.

Studies using surface EEG and MEG as well as intracranial recordings may help to temporally tag the different activations. Of particular importance are findings providing evidence for an early (150-200 msec) involvement of inferior temporo-occipital areas in visual word recognition (Allison et al., 2002; Salmelin et al., 1996; Tarkiainen et al., 1999). Indeed, differential brain electrical responses for pseudowords and pseudohomophones were recently found as early as 150 msec after stimulus onset (Braun et al., 2008).

Baseword Frequency Effect

The strongest evidence for phonologically driven lexico-semantic access in the present study is provided by the observed BFE. Pseudohomophones derived from low frequency basewords evoked greater activation in areas corresponding to those reported for low frequency words. We observed greater activation in the left and right inferior frontal gyrus comprising the pars triangularis and pars orbitalis, the insula, and also the anterior cingulate cortex for pseudohomophones derived from low compared to those from high frequency basewords.

Word frequency effects are commonly interpreted as a marker of lexical processing (e.g., Forster & Chambers, 1973; Sereno, Rayner & Posner, 1998; Hauk & Pulvermüller, 2004). Previous neuroimaging studies associated effects of word frequency mainly with activation in the left inferior frontal gyrus (e.g., Chee et al., 2002; Chee et al., 2003; Keller et al., 2001; Kuo et al., 2003; Hofmann et al., 2008), but also with activation in the fusiform gyrus (e.g., Kronbichler et al., 2004; Joubert et al., 2004; Hauk et al., 2008). Graves et al. (2007) reported left inferior frontal gyrus activation in pars triangularis and orbitalis for the processing of low frequency words in naming words and pictures. This activation was supposed to reflect lexico-semantic and lexico-phonological processing (see also Indefrey & Levelt 2000, 2004, for further evidence in word production). Furthermore, left insula (Rumsey et al., 1997; Fiebach et al., 2002), superior temporal gyrus, inferior and middle temporal, as well anterior cingulate cortex activation was reported to be sensitive to word frequency (e.g., Carreiras et al. 2006; Fiez et al., 1998; Fiebach et al., 2002). Fiez et al. (1998) reported frequency effects in the left superior temporal gyrus, the supplementary motor area and also in the inferior frontal gyrus extending in the anterior insula in reading aloud. Fiebach et al. (2002) found effects in the left inferior frontal gyrus comprising pars opercularis and triangularis as well as the bilateral insula for lexical decisions. These studies consistently revealed greater activation in response to low compared to high frequency words.

As mentioned before, lexical decisions to pseudohomophones are assumed to involve the activation of the underlying baseword representations and thus should reflect access to whole-word representations. Models of visual word recognition implementing interactive activation processes, such as the DRC and the MROM-P, assume that processing is more difficult - entailing more errors and slower response times - for pseudohomophones derived from high than from low frequency basewords. The former are believed to elicit greater activation in a hypothetical phonological lexicon resulting in stronger 'word present' signals. Those therefore should elicit greater activation in regions known to process phonological information. However, the behavioural and imaging results of the present study are against this interpretation. Pseudohomophones from high compared to low frequency basewords are rejected faster and do not evoke greater activation in any brain area. Thus, the current results are in line with earlier findings (e.g., Ziegler et al., 2001), suggesting that decisions to pseudohomophones from low frequency basewords are more difficult. The question is at what level of processing - orthographic, phonological, decision making, response selection or conflict processing - the effect arises.

One explanation for the reversed baseword frequency effect is provided by the spelling-verification hypothesis (e.g., Paap et al., 1982; Ziegler et al., 2001). In contrast to the predictions of a pure activation account of computational models, spelling verification should be more difficult for pseudohomophones from low frequency basewords, because they are believed to have weaker representations in memory. The less often a word is encountered, the less efficient are the connections representing this word and the more activation is necessary to retrieve the corresponding word. Therefore, an orthographic spell-check for pseudohomophones derived from low frequency basewords results in greater activation in regions reflecting orthographic processing.

The left fusiform gyrus is a likely candidate for such a spelling-verification mechanism. The fusiform gyrus is sensitive to the frequency of words, as was demonstrated in greater activation for low than for high frequency words in silent reading (e.g., Kronbichler et al., 2004; see also Joubert et al., 2004). Recently, Hauk, Davis and Pulvermüller (2008) applied multiple linear regression analysis on word frequency, neighbourhood density and orthographic typicality to uncover brain regions involved in silent reading. Word frequency was negatively correlated with the BOLD response (i.e., greater activation for low frequency words) in the left fusiform gyrus as well as in bilateral inferior frontal gyrus and insula, suggesting an involvement in lexical processing. The activation coordinates in the fusiform gyrus were close to the visual word form area as reported in McCandliss, Cohen and Dehaene (2003). In contrast to Kronbichler et al., (2004) and Hauk et al. (2008) we did not find evidence for frequency-related processing of pseudohomophones in the fusiform gyrus . However, activation was greater for pseudohomophones than for pseudowords. Since pseudohomophones and pseudowords did not differ in orthographic similarity it is unlikely that this activation difference is due to orthographic word-form processing.

Therefore, we propose that the fusiform gyrus is not sensitive to baseword frequencies, given that spelling-verification is an active mechanism in pseudo-homophone processing. The neuroimaging results revealed greater activation for pseudohomophones from low frequency basewords in areas of the inferior frontal gyrus that were previously linked to lexico-semantic processing (e.g., Mechelli et al., 2007; Nixon et al., 2004; Devlin, Matthews & Rushworth, 2003; Gold et al., 2005) involving processes of lexical search and selection (e.g., Fiebach et al., 2002; Thompson-Schill et al., 1997; Poldrack et al., 1999). In particular, activation was higher in pars triangularis and orbitalis and insula on the left, in pars orbitalis and insula on the right, as well as left and right anterior cingulate. Under the assumption that pars orbitalis and pars triangularis reflect lexical or whole-word form processing and that a spell-check is necessary for a lexical decision to pseudohomophones, it seems suitable to draw the conclusion that such a spell-check operates at the whole word-level by comparing the pseudohomophones with their baseword representations stored in memory.

Concerning a specific role of the left inferior frontal gyrus in semantic processing, Poldrack et al. (1999) proposed that it serves as semantic working memory or executive system rather than as storage for semantic knowledge (e.g., Gabrieli et al., 1996; Kapur et al., 1994). Poldrack et al. argued that the functional role of such a system may be to access, maintain, and manipulate semantic representations which are probably stored in the temporal cortex. Furthermore, Hagoort (2005) proposed a psycholinguistic framework of language production and comprehension relating the processing steps to the left inferior frontal gyrus. The framework comprises three functional components of language processing: memory, unification, and control (MUC). The memory component accomplishes specification of stored information and operations of retrieval. Unification refers to the integration of retrieved lexical information into larger structures, by combining information about phonology, syntax and meaning retrieved from memory. Finally, the control component relates language to action. Hagoort proposed that the left inferior frontal gyrus comprising pars opercularis, triangularis and orbitalis and the ventral part of the supplementary motor area are the language-relevant parts of the prefrontal cortex. This area is supposedly concerned with operations of integration. A first important function is to preserve information online for further processing and a second is to select among competing alternatives. Hagoort reports evidence for syntactic and semantic unification in the left inferior frontal gyrus (e.g., Indefrey et al., 2004; Hagoort et al., 2004), but evidence for phonological unification in the left inferior frontal gyrus still needs to be provided. Given the substantial overlap of these areas in the processing of semantic, syntactic and phonological processing in previous research, Hagoort argues that there is a possibility of interactive concurrent processing in the left inferior frontal gyrus incorporating various types of processing constraints as soon as they become available. Despite the fact that the MUC framework is designed for multi-word processing, we propose that activation difference in the left inferior frontal gyrus for pseudohomophones compared to pseudowords in the present study may reflect processes of unification in single word processing. Activation in the left and right inferior frontal gyrus probably reflect both processes of lexical selection (Fiebach et al., 2002) as well as the combination of individual pieces of orthographic and phonological information into a representational structure in the sense proposed by Hagoort.

Processing of Conflict

Anterior cingulate cortex and supplementary motor area activation in studies of visual word recognition is often assumed to reflect conflict processing (Carreiras et al., 2006; Fiebach et al., 2007). Consistent with this view, the observed activation in the anterior cingulate cortex for the comparison of pseudohomophones and pseudowords (PHE) and of pseudohomophones from high and low frequency basewords (BFE) may reflect processes of response selection and/or of conflict monitoring or regulation.

Bitan et al. (2007) manipulated orthographic and phonological similarity between visually presented word pairs and compared conflicting and non-conflicting conditions in spelling and rhyme judgements. They found greater activation for the conflicting phonological condition in the bilateral inferior frontal gyrus. This activation was regarded as repetitive mapping between orthography and phonology, such that increased phonological segmentation and covert articulation is necessary to verify the accuracy of the outcome. Bitan et al. proposed competition at two stages when readers encounter conflict between orthographic and phonological information. Conflict arising at an early stage, like the generation of or access to a representation, is located in the left inferior frontal gyrus. Later conflict processing comprises response selection located in the anterior cingulate and medial frontal cortex.

Recently, van Heuven et al. (2008) investigated cross-language interference in the bilingual brain and reported pre-frontal cortex activation. Van Heuven et al. presented English-Dutch interlingual homographs to Dutch bilinguals in two tasks. In the English lexical decision task participants decided if a presented homograph was an English word or not. Two sources of conflict were assumed: one at the level of stimulus materials i.e., interference of language 1 (L1) with language 2 (L2) and a second source at the response level. In the general lexical decision task, participants decided if the presented homograph was a word or not. Here stimulus-based conflict but no response conflict should occur since items processed in either language lead to the same response. Left inferior pre-frontal cortex (pars opercularis and orbitalis) activation was found for both tasks and was interpreted as stimulus-based conflict between the first and the second language. In contrast, activation in the supplementary motor area and the anterior cingulate was only found in the English lexical decision task, where a response conflict was expected in addition to the stimulus-based conflict. Therefore, van Heuven et al. proposed that activation in the supplementary motor area is involved in executive control processes that are recruited to solve response-based language conflict and that the anterior cingulate is sensitive to conflict in relation to action (response conflict), but not to stimulus conflict. In contrast, Roelofs, van Turennout and Coles (2007) reported activation in the anterior cingulate cortex even in the absence of response conflict in Stroop-like tasks and proposed conflict regulation rather than response conflict as the underlying process.

As stated above, we assume that lexical decisions to pseudohomophones are in general more demanding than to pseudowords because of conflicting information in the hypothetical phonological and orthographic lexicons. Therefore, the comparison of pseudohomophones and pseudowords as well as of pseudohomophones from low and high frequency basewords should produce greater activation in regions hosting these lexicons and/or in regions reflecting conflict processing. The results of our study therefore provide insights about the likely locus of this kind of processing. We propose that pseudohomophones require processing at a lexical as well as at post-lexical levels. Activation of the left and right inferior frontal gyrus signals phonology-driven lexical processing involving access, selection and manipulation of orthographic and phonological lexico-semantic information. Anterior cingulate cortex activation probably signals post-lexical processing, involving conflict monitoring, response selection and conflict regulation. Additional evidence for such an interpretation was recently provided by Fiebach et al. (2007), who reported anterior cingulate cortex activation in lexical decision for words and nonwords with high and low numbers of orthographic neighbours in visual word recognition. Fiebach et al. proposed that this activation is likely to reflect a domain general extra-lexical process which serves important executive control functions during visual word recognition.

Conclusion

The present study used the PHE and the BFE to investigate brain responses to phonological processing in visual word recognition. We propose that pseudohomophones activate whole-word representations of their phonological identical basewords signalling access at the lexical level. Furthermore, activation differences observed for pseudohomophones derived from basewords of high and low frequency are in favour of phonologically driven lexical access and therefore of models of visual word recognition that implement frequency-sensitive representations. Reading pseudohomophones seems to involve the same kind of processing as word reading as evidenced by activation in the same brain areas. Thus, reading probably comprises three stages of processing: (1) pre-lexical analysis of the visual word-form and early lexical processing in the fusiform gyrus, (2) access to orthographic, phonological, and semantic features in the middle and superior temporal, angular and supramarginal gyri, and (3) manipulation of these features in the inferior frontal gyrus involving processes of orthographic-phonological mapping, lexical search and retrieval. Processing specific to pseudohomophones and pseudowords presumably involves a spelling-verification mechanism which is likely to work on whole-word forms and is associated with the inferior frontal gyrus. Furthermore, supplementary motor area and anterior cingulate activation probably signal processes of conflict monitoring, conflict regulation, and response selection imposed by the lexical decision task and linguistic stimulus processing.

General Discussion

In 1995 Jacobs and Carr speculated about the possibility of bridging the gap between computational models of word recognition and data obtained from electrophysiological and brain imaging studies. In particular, they stated that models of the interactive activation family are able to make relatively precise predictions about (1) the total amount of activity that should occur within the orthographic processing system, (2) the total number of word representations within the system that should be activated, and (3) the relative degree of activation of each representation, given the familiarity, orthographic structure, and similarity or neighbourhood organisation of a particular word being processed.

Under the assumption that the amount or the spread of computational activation could be related to that of neural activation, predictions can be made from computational models of orthographic and phonological processing to the neural measurement of activation within the brain structures thought to support that processing. Thus, activation obtained in simulations of models of visual word recognition could be used to make predictions about the corresponding brain activation and this would evaluate both the computational models of cognitive processing and the neurocognitive model of functional anatomy.

A few steps in this direction can be found in the literature on word recognition. Two examples from electrophysiological and neuroimaging research are the studies of Holcomb, Grainger and O’Rourke (2002) and Binder et al. (2003) reported in the present Study 1. Both studies tested – more or less directly – predictions of interactive activation (localist connectionist) models of word recognition and used them for interpreting their data. In particular, assumptions were tested that related the amount of activation generated in a hypothetical mental lexicon depending on the size of the orthographic neighbourhood of letters strings to recorded brain activation, thus, closely following Jacobs' and Carr's earlier speculations.

In any case, the above studies are encouraging in terms of the proposals of Jacobs and Carr. However, both studies tested predictions of computational models more indirectly and in a dichotomous/qualitatively way. They used the N-Metric (Coltheart et al., 1977) to operationalise the global lexical activation generated by letter strings in simulation models such as the MROM or the revised DRC model (Coltheart et al., 2001) and 2 x 2 designs with stimuli having either small or large neighbourhoods.

Study 1 was designed to extend those findings by providing a more direct neurocognitive test of the MROM. The idea was to directly determine the hypothetical amount of lexical activation generated by letter strings by running simulations using the MROM and then examine to what extent behavioural and brain-electrical parameters correlate with variations in simulated global lexical activation levels.

The results of Study 1 revealed that the grade of orthographic-phonological similarity of the stimulus material lead to a gradual brain response to pseudowords. Pseudowords with high levels of orthographic-phonological similarity elicited a more negative response than pseudowords with low levels of orthographic-phonological similarity in an ERP component starting at 400 msec after stimulus onset. Furthermore, an effect of lexicality was observed. At around 300 msec, brain responses to pseudowords started to be more negative than to words. These findings were interpreted to reflect two decision processes predicted by the MROM. A first process based on local lexical activation for words and a second process reflecting global lexical activation and unsuccessful lexical access in response to pseudowords. The first process was interpreted as reflecting the identification process and the second was proposed as potentially reflecting the deadline process predicted by the MROM. In addition, Study 1 revealed no evidence for the existence of an early familiarity process as proposed by the MROM.

Processing of single words in a lexical decision task therefore seems to involve a first process of mapping words onto already stored representations in memory and a later process of ongoing processing and abortion if no matching representation could be found. Letter strings, having a high orthographic-phonological similarity (lexical similiarity) are proposed to map easily onto stored representations. Those which are low in orthographic-phonological similarity are supposed to be easy to reject, because there is relatively little global lexical activation. In contrast, words with low levels of lexical familiarity are harder to map because their representations in memory are weaker and/or noisier. Pseudowords with high levels of orthographic-phonological similarity are supposed to be hard to reject, since global lexical activation (familiarity) is high, making the identification as a pseudoword harder and thereby prolonging processing time.

Study 1 thus showed that the orthographic-phonological structure of words and pseudowords can systematically be related to the brains electrical activity. Study 2 aimed at a more explicit test of the time course of phonological processing and the predictions of the MROM-P by using the lexical decision task, the pseudohomophone effect, event-related potentials and low resolution brain electromagnetic tomography.

The standard explanation for the pseudohomophone effect is that a given pseudohomophone activates the representation of its phonologically identical word in the phonological lexicon. Thus, the phonological lexicon signals the presence of a word, but the orthographic lexicon signals its absence. In lexical decision it is assumed that resolving this conflict takes time. Subjects show longer latencies in the rejection of pseudohomophones than in the rejection of pseudowords. The pseudohomophone effect occurs either because the phonological code is associated with the word and/or because the pseudohomophones activate semantic information associated with the baseword from which the pseudohomophone was derived. Thus, the pseudohomophone effect describes the fact that in a task which theoretically does not require any phonological processing, phonological processing is automatically active. There is evidence that not all readers show phonological interference. Ziegler, Jacobs and Klüppel (2001) showed that fast subjects in their study did not show a pseudohomophone effect which means that they possibly made their decisions without processing phonological information. They might rely solely on orthographic information or on semantic information activated from orthography. A second possibility is that the fastest subjects also activate phonological information in performing the task to some minor such that this information did not interfere with making the response.

The pseudohomophone effect was found in English, French as well as in German which indicates that not only relatively consistent languages like German show such phonological interference effects. Furthermore, Ziegler et al. (1997) extended the effect to English homophones (words that sound alike, e.g., HALE and HAIL). The extension to homophones made clear that phonological interference effects are not restricted to artificial words, but are in effect in everyday word recognition suggesting a universal phonological process. Further research showed that the pseudohomophone effect is modulated by some variables like orthographic similarity and phoneme spelling probability, but to be independent from word length in 3-5 monosyllabic words (see Klüppel, 1998 and Ziegler, et al., 2001, for influencing variables on the pseudohomophone effect).

These and other not reported findings (see Klüppel, 1998) support the hypothesis of phonological recoding in silent reading in a sophisticated fashion: in visual word recognition tasks which do not afford phonological recoding, phonological and orthographic processes interact in a complex and subtle way. Phonological recoding seems not to be influenced by simple factors such as word length, but to be prone to the influence of higher-level-factors such as orthographic-phonological similarity or dominance of phoneme spellings. It seems that users of different languages are sensible to the grapheme-phoneme and phoneme-grapheme relations in their respective languages and that these affect the degree of phonological recoding. Therefore, the above reported findings indicate that phonological processing is a general mechanism in visual word recognition.

The pseudohomophones in Study 2 elicited the slowest lexical decision times and less positive brain responses than pseudowords in the P150 ERP component. This P150 was interpreted as the brain-electrical response to the conflict between orthographic and phonological word representations in memory. Furthermore, the co-occurrence of the word frequency effect in Study 2 in nearly the same time window favours an interpretation of a lexical locus of the observed pseudohomophone effect. This finding adds further support to the claim that phonological activation occurs early enough to affect lexical access. Effects of word frequency are interpreted as an upper limit for lexical access (e.g., Forster & Chambers, 1973; Hauk & Pulvermüller, 2004; Rubenstein et al., 1970; Sereno et al., 1998, but see Balota & Chumbley, 1984, for a different view). According to current models of visual word recognition word, frequency is believed to determine the availability of lexical representations by affecting the resting levels of these representations. Therefore, high-frequency words should be responded to faster in lexical decision because their representations have higher resting levels than low-frequency words. The early effect of word frequency suggested that lexical access from written words can occur as early as 150 msec after stimulus presentation. Thus, lexical processing of words is under way at least before the N400 component. Words in Study 2 started to differ from nonwords (pseudohomophones and pseudowords) from 260 msec post-stimulus onwards, peaking at 400 msec.

The results of the source analysis supported the ERP findings suggesting an early involvement of phonological processing in visual word recognition. The contrast of pseudohomophones and pseudowords showed the largest differences in a left temporo-parietal region comprising the supramarginal gyrus (Brodmann Area 40) and in a right fronto-temporal area at the border of the inferior frontal gyrus (Brodmann Areas 44, 45), the insula (Brodmann Area 13), the supplementary motor area (Brodmann Area 6), and the superior temporal gyrus (Brodmann Area 22). Results of previous neuroimaging studies suggested that the supramarginal gyrus, the pars triangularis, and the supplementary motor area are part of Baddeley's phonological loop (Baddeley, 1986) linking inferior frontal activation to articulatory rehearsal and supramarginal gyrus activation to phonological storage (Demonet et al., 1994; Gold & Buckner, 2002; Paulesu et al., 1993; Tan et al., 2005).

In sum, Study 2 revealed that phonological processing influenced word processing at an early processing stage. The assumption that phonological processing occurs rather late – usually after syntactic and semantic processing – could be rejected. Furthermore, the source analysis revealed that left temporo-parietal (supramarginal gyrus) and right fronto-temporal areas (inferior frontal gyrus, insula and the superior temporal gyrus) were involved in phonological processing at the lexical level at this early point in time. These results added further support to the notion of an early mapping between orthography and phonology as an integral part of lexical access and thus provided evidence for the phonological mediation hypothesis.

Study 3 extended the investigation of orthographic and phonological processing by using again the lexical decision task and the pseudohomophone effect.

Furthermore, the baseword frequency effect was used to tap deeper into phonological processing and its role in lexical access. The attempt was made not only to replicate the pseudohomophone effect, but also to find a possible factor that modulates the size of this effect i.e. baseword frequency was manipulated. The hypothesis was that if baseword frequency modulates the size of the pseudohomophone effect this should provide additional evidence for the idea that phonological processing is involved in lexical access. To obtain a more detailed picture of the involved brain areas fMRI was used. The behavioural and neuroimaging results suggested that pseudohomophones indeed activated their baseword representations at a lexical level. Phonological processing as indexed by the baseword frequency effect was accompanied by bilateral frontal (inferior frontal gyrus, Broca, cingulate cortex), but also left lateralised parietal-temporal activation (Wernicke, angular and supramarginal gyrus) as well as left occipito-temporal (fusiform gyrus) activation.

It was hypothesised that reading pseudohomophones recruits very similar processes as reading words and that reading probably comprises three neurocognitive stages: (1) pre-lexical analysis of the visual word-form and early lexical processing in the fusiform gyrus, (2) access to orthographic, phonological, and semantic features in the middle and superior temporal gyrus as well as the angular and supramarginal gyrus, and (3) manipulation of these features in the inferior frontal gyrus involving processes of orthographic-phonological mapping, as well as processes of lexical search and retrieval.

The temporal resolution of brain imaging data used in Study 3, did not allow for a decision as to whether the observed differences in neural activation elicited by pseudohomophones and pseudowords in temporo-parietal and inferior frontal areas were due to initial phonological processing after early visual feature extraction or whether they were due to the modulation of these areas during later processing. Yet, evidence for an early processing of linguistic stimuli was provided by studies using surface EEG and magneto-encephalography (MEG) as well as intracranial recordings (e.g., Allison et al., 2002; Salmelin et al., 1996; Tarkiainen et al., 1999). These studies showed that inferior temporo-occipital areas are involved in early visual word recognition (150-200 msec). Furthermore, the results of Study 2 support early phonological processing hypothesis by showing differential brain electrical responses for pseudowords and pseudohomophones as early as 150 msec post-stimulus (Braun et al., in press).

Furthermore, Study 3 revealed anterior cingulate cortex and supplementary motor area activation. This was interpreted to reflect processes of response selection and/or of conflict monitoring in response to pseudohomophones and pseudowords and to pseudohomophones of different baseword frequencies (e.g., Bitan et al., 2007; van Heuven et al., 2008; Carreiras et al., 2006; Fiebach et al., 2007). In order to accomplish lexical decisions to pseudohomophones and pseudowords an orthographic spelling verification mechanism was proposed (cf. Paap et al., 1982; Ziegler et al., 2001). If such a mechanism is active in visual word recognition it is likely to work on whole-word forms and proposed to be associated with activation in the inferior frontal gyrus.

The pseudohomophone effect is consistently found to be strongest for low frequency items (Ziegler et al., 2001); this was replicated in Study 2 and 3. Furthermore, the finding that subjects which are fast in making lexical decisions did not show a pseudohomophone effect could suggest that these experienced readers do use a direct route from orthography to meaning and that phonological mediation is strongest when things become difficult like in the case of pseudohomophones or homophones or when context and semantics do not provide sufficient information.

Furtermore, clinical evidence suggests the existence of different pathways in reading that can lead to correct word identification. Research on dyslexia has proposed two distinct subtypes of developmental dyslexia (for a different opinion see Van Orden, Pennington, & Stone, 1998). The two forms differ in the involvement of phonology in reading. Surface dyslexics would be impaired in tasks involving orthographic knowledge, but not involving phonology. Phonological dyslexics are reported to show the opposite pattern (Manis & Seidenberg, 1996). Surface dyslexics are therefore thought to rely solely on phonological strategies in reading (see Caccapolo-van Vliet, Miozzo, & Stein, 2004, for a different view).

Despite the evidence from clinical studies and the research on normal adults for two pathways in reading, phonological recoding is probably not superfluous for optimal reading performance. Beginning readers rely heavily on phonology (Alario et al., 2007; Bosman & de Groot, 1996; Goswami et al., 2001; Jacobs, 2002; Ziegler & Goswami, 2005). If this first language code is displaced later during more reading experience by a strong automaticity of orthographic processing allowing for reading for comprehension is still an unanswered question. There is evidence that the phonological system serves as a backup system which is critical for the speed and the accuracy of word recognition. Moreover, phonology probably provide a means of expanding the online memory for individual words as it is essential for text comprehension (e.g., Vallar & Baddeley, 1987). Recent findings suggested that this could be a by-product of a more general function of the phonological loop (Baddeley, 1986) which is now proposed to have evolved to store unfamiliar sound patterns while more permanent memory records are being constructed and therefore to mediate language learning (Gathercole & Baddeley, 1993; Baddeley, 2003).

Concerning models of word recognition, most models are not explicit in the time course of the processes involved in word recognition. In the cohort model of Marslen-Wilson (1987) the identification of words is assumed to happen at around 200 msec. But it is not clear if the model makes any predictions about the latency of a component which correlates with the frequency of words. Another model with timing information is the model of picture naming from Levelt, Roelofs, and Meyer (1999). They proposed a time course of lexical access starting with visual processing from 0 to 150 msec, followed by lemma selection from 150 to 275 msec, and phonological encoding in a time window from 275 to 400 msec which is much later than found in Study 2.

The present results support predictions of the MROM-P and challenge all models of visual word recognition that do not include an automatic phonological recoding process. Furthermore, the MROM-P as well as the DRC already simulated the pseudohomophone effect and predicted the baseword frequency effect. However the predictions were in the wrong direction: pseudohomophones of low frequency basewords were harder to reject than those of high frequency basewords. Further research is necessary to decide between an activation and a verification account.

Parallel distributed models as the PMSP of Plaut et al. (1996) have an even harder time to account for the baseword frequency effect. In a distributed system words do not have corresponding whole-word representations stored in the network. Thus, whether a nonword sounds like a word is irrelevant to performance. Instead, processing of nonwords in the orthography-to-phonology network is determined by how closely the spelling-to-sound mappings resemble those of real words. Seidenberg et al. (1996) assumed that in naming the pseudohomophone effect reflects the familiarity of post-lexical mappings between phonological and articulatory units. Pseudohomophone effects are not produced within the orthography-to-phonology network that encompasses lexical effects; therefore the processing of pseudohomophones should not be affected by the frequency of the corresponding basewords. Thus, the results of Study 2 and 3 are in favour of models of visual word recognition that assume an involvement of phonological information in visual word recognition as well as of models that assume frequency sensitive representations of words. Thus, it is still a matter of debate how words are represented in the brain. However, there is agreement that normal language comprehension and production is not possible without an efficiently organised mental store.

An assumption of Study 2 and 3 was that processing of pseudohomophones is more demanding than processing of pseudowords. Pseudohomophones should produce conflicting activation in the phonological and orthographic lexicons. Therefore, pseudohomophones should produce higher activation in regions believed to process this information and/or in regions that are known to reflect conflict processing. The results of Study 2 and 3 should therefore provide an answer to the locus of this kind of conflict processing, if it is located at a lexical or at an extra-lexical level or both. Processing of pseudohomophones was proposed to involve a pre-lexical analysis of the visual word-form and early lexical processing in the fusiform gyrus. Access to orthographic, phonological, and semantic features seem to be performed in the middle and superior temporal gyrus as well as the angular and supramarginal gyrus. Further processing of these features is likely to be performed in the inferior frontal gyrus involving processes of orthographic-phonological mapping as well as the processing of the conflicting information elicited in the orthographic and phonological lexicons. Activation in the anterior cingulate cortex and the supplementary motor area is proposed to signal processes of response selection and/or of conflict monitoring and to reflect extra-/post-lexical levels of conflict processing and to follow the linguistic conflict processing.

In sum, the three studies of this thesis revealed that models of visual word recognition can make useful predictions about cognitive processing which could empirically be tested in both behavioural and neurocognitive experiments. Phonological processing seems to occur much earlier as previously assumed and to guide lexical access by facilitating access to whole-word forms and to involve left temporo-parietal, temporo-occipital and inferior frontal brain regions.

Outlook

Further research in visual word recognition could profit from the combination of neurocognitive methods available to disentangle the processes involved in reading and their interactions. The combination of EEG and fMRI as well as Eyetracking and EEG or Eyetracking and fMRI should provide deeper insights into reading-related brain structures and the time course of reading. Furthermore, reading research should study this process in more natural, ecologically more valid settings. Reading whole sentences as well as whole texts is required to investigate the higher-level processes (semantic, syntax, orthography, phonology, emotion, etc.) and their interactions in reading for comprehension. To get to this point – the methods of EEG and fMRI have to be enhanced. For example, until now ERP measures are recorded stimulus-locked and in a serial item-by-item fashion. Recent developments in ERP measurement provide a more ecological approach. Hutzler et al. (2007) used the point in time when the eye fixates a presented stimulus as the marker for the onset of cognitive processing. These fixation related potentials (FRPs) allow for a closer link of perception and cognitive-linguistic processing in future research.

Concerning fMRI, a recently introduced method by Yarkoni et al. (2008) revealed promising results for the study of word-level processes with fMRI within narrative reading contexts. The event-related reading (ERR) approach makes use of the finding that the hemodynamic response after visual stimulation has been shown to sum approximately linearly even at short durations (Burock et al., 1998). Using multiple regressions on 12 variables known to have an impact on visual word recognition, Yarkoni et al. showed that this new method delivered comparable results previously obtained with single word presentations and that this method could be used to investigate also complex stimuli like words.

The aim of the studies of this thesis was to add further knowledge about the complex structure and performance of the human brain while reading words and nonwords. Combining the methods of experimental psychology and psycholinguistics with the developments of neurocognitive methods seems to be a fruitful way of studying human behaviour and thus to allow for further progress in the research of human brain functions.

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Appendix A. Stimuli of Study 1

items	lexicality	Msom	ops
ACHT	word	0.21	4
APUK	nonword	0.11	1
AROT	nonword	0.21	2
ARZT	word	0.21	4
AUCH	word	0.28	6
AUCK	nonword	0.20	2
AUHT	nonword	0.16	1
BAAN	nonword	0.20	2
BACH	word	0.31	6
BAHN	word	0.28	6
BALK	nonword	0.24	3
BALL	word	0.29	6
BAML	nonword	0.25	3
BANG	word	0.35	6
BANK	word	0.30	6
BART	word	0.27	6
BAUB	nonword	0.23	2
BAUM	word	0.28	6
BAUN	nonword	0.24	3
BEEG	nonword	0.17	1
BEET	word	0.21	4
BELT	nonword	0.23	2
BENG	nonword	0.18	1
BERG	word	0.20	4
BERL	nonword	0.20	2
BERV	nonword	0.19	1
BETA	nonword	0.14	1
BETT	word	0.29	6
BEXZ	nonword	0.15	1
BIER	word	0.31	6
BILD	word	0.26	5
BILZ	nonword	0.22	2
BJCK	nonword	0.16	1
BLAF	nonword	0.15	1
BLAU	word	0.20	4
BLEG	nonword	0.14	1
BLUK	nonword	0.16	1
BLUT	word	0.25	5
BMCH	nonword	0.19	1
BOCK	word	0.25	5

items	lexicality	Msom	ops
BOFT	nonword	0.22	2
BOOD	nonword	0.18	1
BOOM	nonword	0.16	1
BOOT	word	0.20	4
BRAN	nonword	0.22	2
BRAV	word	0.16	4
BREH	nonword	0.18	1
BROT	word	0.25	5
BRUZ	nonword	0.15	1
BUCH	word	0.30	6
BUDT	nonword	0.20	2
BUNS	nonword	0.20	2
BUNT	word	0.23	4
BURG	word	0.23	4
BVAV	nonword	0.11	1
CHOR	word	0.20	4
CHOS	nonword	0.11	1
DACH	word	0.31	6
DAGD	nonword	0.19	1
DANM	nonword	0.23	2
DARK	nonword	0.22	2
DAST	nonword	0.28	3
DEHN	nonword	0.22	2
DEIS	nonword	0.23	2
DIBL	nonword	0.14	1
DICK	word	0.26	5
DIEB	word	0.26	5
DIEH	nonword	0.22	2
DILL	word	0.18	4
DING	word	0.23	5
DJRT	nonword	0.15	1
DLUT	nonword	0.20	2
DNMM	nonword	0.16	1
DOFT	nonword	0.18	1
DOOF	word	0.20	4
DORB	nonword	0.25	3
DORF	word	0.27	6
DORV	nonword	0.21	2
DOUK	nonword	0.16	1
DREI	word	0.26	1

items	lexicality	Msom	ops
DRIM	nonword	0.16	1
DUAT	nonword	0.18	1
DUFT	word	0.23	4
DUHN	nonword	0.17	1
DUMM	word	0.19	4
DVUM	nonword	0.14	1
EALD	nonword	0.21	2
EANF	nonword	0.22	2
ECHT	word	0.20	4
EIEB	nonword	0.23	2
EINS	word	0.23	5
ELCH	word	0.21	4
ELCK	nonword	0.17	1
ELCO	nonword	0.12	1
ERDT	nonword	0.15	1
ERUT	nonword	0.18	1
ERZT	nonword	0.17	1
ESNS	nonword	0.12	1
EUCW	nonword	0.14	1
EUFT	nonword	0.17	1
FACH	word	0.29	6
FAEH	nonword	0.15	1
FAIN	nonword	0.23	2
FALB	nonword	0.20	2
FALG	nonword	0.22	2
FALL	word	0.29	6
FARS	nonword	0.23	3
FATT	nonword	0.22	2
FAUL	word	0.28	6
FAUM	nonword	0.28	3
FAUN	word	0.24	5
FBON	nonword	0.13	1
FEHD	nonword	0.18	1
FEIG	word	0.25	5
FEIL	word	0.34	6
FEIZ	nonword	0.25	3
FELB	nonword	0.23	2
FELD	word	0.28	6
FELM	nonword	0.24	3
FELS	word	0.25	5

items	lexicality	Msom	ops
FERD	nonword	0.21	2
FERH	nonword	0.23	2
FERL	nonword	0.24	3
FERM	nonword	0.22	2
FERZ	nonword	0.22	2
FETT	word	0.29	6
FFLZ	nonword	0.15	1
FGOR	nonword	0.13	1
FILG	nonword	0.18	1
FILM	word	0.20	4
FILZ	word	0.25	5
FIND	nonword	0.26	3
FINK	word	0.25	5
FIOK	nonword	0.14	1
FIRB	nonword	0.17	1
FIRN	word	0.25	5
FLAB	nonword	0.18	1
FLAF	nonword	0.17	1
FLAU	word	0.25	5
FLOH	word	0.22	4
FLUG	word	0.26	5
FLUH	nonword	0.22	2
FLUN	nonword	0.22	2
FLUR	word	0.25	5
FLUT	word	0.27	6
FMND	nonword	0.20	2
FOOR	nonword	0.16	1
FORM	word	0.26	5
FPUR	nonword	0.16	1
FRAU	word	0.23	5
FRAV	nonword	0.17	1
FREC	nonword	0.14	1
FREI	word	0.24	5
FROH	word	0.22	4
FROP	nonword	0.16	1
FROT	nonword	0.20	2
FRST	nonword	0.25	3
FRUT	nonword	0.21	2
FSIG	nonword	0.12	1
FUHZ	nonword	0.13	1

items	lexicality	Msom	ops
FULK	nonword	0.14	1
FUNS	nonword	0.18	1
FURD	nonword	0.21	2
FVUL	nonword	0.14	1
GAIS	nonword	0.20	2
GAND	nonword	0.32	3
GANQ	nonword	0.21	2
GANS	word	0.26	5
GANZ	word	0.26	5
GARL	nonword	0.27	3
GARM	nonword	0.24	3
GAST	word	0.30	6
GEIZ	word	0.24	5
GEJN	nonword	0.19	1
GELB	word	0.23	5
GELD	word	0.29	6
GENZ	nonword	0.20	2
GERN	word	0.27	6
GEUL	nonword	0.22	2
GGOB	nonword	0.12	1
GIEG	nonword	0.19	1
GIFT	word	0.20	4
GILS	nonword	0.19	1
GINS	nonword	0.22	2
GIPS	word	0.19	4
GIRN	nonword	0.22	2
GKNZ	nonword	0.14	1
GLAL	nonword	0.17	1
GLAS	word	0.20	4
GLUR	nonword	0.17	1
GNOM	word	0.14	4
GOLB	nonword	0.20	2
GOLD	word	0.27	6
GOLF	word	0.23	5
GOLK	nonword	0.20	2
GOOT	nonword	0.18	1
GORN	nonword	0.27	3
GRAF	word	0.31	6
GRAS	word	0.31	6
GRAU	word	0.31	6

items	lexicality	Msom	ops
GRID	nonword	0.15	1
GROB	word	0.20	4
GROT	nonword	0.20	2
GRST	nonword	0.21	2
GRZT	nonword	0.18	1
GUAU	nonword	0.15	1
GULL	nonword	0.20	2
GURT	word	0.21	4
GUTT	nonword	0.22	2
HAAD	nonword	0.22	2
HAAR	word	0.21	4
HAAT	nonword	0.28	3
HADT	nonword	0.25	3
HAGS	nonword	0.20	2
HAHN	word	0.30	6
HAIM	nonword	0.24	3
HAIN	word	0.24	5
HALD	nonword	0.31	3
HALR	nonword	0.27	3
HALS	word	0.29	6
HALT	word	0.32	6
HAMB	nonword	0.19	1
HAMN	nonword	0.23	2
HAND	word	0.33	6
HANF	word	0.23	5
HANN	nonword	0.31	3
HART	word	0.32	6
HAST	word	0.33	6
HATN	nonword	0.23	3
HAUL	nonword	0.26	3
HAUS	word	0.30	6
HAUT	word	0.30	6
HAWD	nonword	0.26	3
HEET	nonword	0.21	2
HEFT	word	0.20	4
HEHN	nonword	0.24	3
HEIL	word	0.33	6
HEIM	word	0.28	6
HEJR	nonword	0.22	2
HEKR	nonword	0.22	2

items	lexicality	Msom	ops
HELD	word	0.30	6
HELM	word	0.27	6
HELS	nonword	0.24	3
HEMD	word	0.23	5
HENB	nonword	0.20	1
HEQD	nonword	0.21	2
HERD	word	0.29	6
HERR	word	0.29	6
HERZ	word	0.29	6
HEUR	nonword	0.22	2
HIEB	word	0.28	6
HIEM	nonword	0.19	1
HIEU	nonword	0.19	1
HIRN	word	0.27	6
HIRZ	nonword	0.22	2
HIST	nonword	0.23	3
HOCK	nonword	0.25	3
HOFT	nonword	0.21	2
HOHL	word	0.27	6
HOLZ	word	0.20	4
HORF	nonword	0.24	3
HPHN	nonword	0.20	2
HRLL	nonword	0.18	1
HUEF	nonword	0.17	1
HUFT	nonword	0.24	3
HUHN	word	0.23	4
HUND	word	0.32	6
HURN	nonword	0.22	2
HVRT	nonword	0.21	2
HWRM	nonword	0.19	1
JACH	nonword	0.27	3
JAGD	word	0.20	4
JAHR	word	0.24	5
JANG	nonword	0.30	3
JART	nonword	0.23	2
JEHL	nonword	0.20	2
JELD	nonword	0.21	2
JERZ	nonword	0.20	2
JETT	nonword	0.25	3
JOCK	nonword	0.25	3

items	lexicality	Msom	ops
JUNG	word	0.20	4
KAAG	nonword	0.20	2
KAFF	word	0.20	4
KAGL	nonword	0.24	3
KAHN	word	0.28	6
KAIF	nonword	0.18	1
KALB	word	0.26	5
KALD	nonword	0.25	3
KALK	word	0.23	5
KALT	word	0.27	5
KALX	nonword	0.21	2
KAMM	word	0.25	5
KAND	nonword	0.31	3
KARG	word	0.20	4
KARM	nonword	0.26	3
KARR	nonword	0.24	3
KAUK	nonword	0.22	2
KAUS	nonword	0.28	3
KAVT	nonword	0.25	3
KEKS	word	0.19	4
KERG	nonword	0.22	2
KERL	word	0.23	4
KERT	nonword	0.20	2
KIEL	word	0.27	5
KIES	word	0.23	4
KIMD	nonword	0.15	1
KIND	word	0.28	6
KINN	word	0.26	5
KITZ	word	0.25	5
KLAR	word	0.17	4
KLEE	word	0.19	4
KLON	word	0.16	4
KLUB	word	0.20	4
KLUF	nonword	0.20	2
KLUG	word	0.25	5
KNBE	nonword	0.10	1
KNIE	word	0.16	4
KNIM	nonword	0.16	1
KOCH	word	0.31	6
KOHL	word	0.26	5

items	lexicality	Msom	ops
KOKS	word	0.19	4
KOLF	nonword	0.20	2
KOPF	word	0.23	5
KORB	word	0.25	5
KORK	word	0.25	5
KORV	nonword	0.24	3
KORZ	nonword	0.24	3
KRAF	nonword	0.20	1
KRAK	nonword	0.18	1
KRAM	word	0.24	5
KRAN	word	0.24	5
KRAR	nonword	0.20	1
KRIL	nonword	0.16	1
KRUG	word	0.22	4
KUET	nonword	0.19	1
KULD	nonword	0.25	3
KULT	word	0.23	4
KUPF	nonword	0.19	1
KURS	word	0.21	4
KURZ	word	0.23	5
KUST	nonword	0.25	3
LACK	word	0.24	5
LAHM	word	0.26	5
LAMM	word	0.25	5
LAND	word	0.32	6
LANS	nonword	0.23	2
LATZ	word	0.20	4
LAUB	word	0.29	6
LAUD	nonword	0.25	3
LAUF	word	0.28	6
LAUG	nonword	0.25	3
LAUM	nonword	0.29	3
LAUN	nonword	0.25	3
LAUR	nonword	0.23	2
LAUT	word	0.29	6
LAUZ	nonword	0.25	3
LEER	word	0.26	5
LEHM	word	0.22	4
LEID	word	0.27	6
LEIM	word	0.30	6

items	lexicality	Msom	ops
LEIN	nonword	0.39	3
LEIZ	nonword	0.27	3
LENZ	word	0.17	4
LIEB	word	0.27	6
LIED	word	0.26	5
LIEI	nonword	0.18	1
LIFT	word	0.25	5
LIST	word	0.28	6
LOHN	word	0.26	5
LUFT	word	0.25	5
LUHM	nonword	0.19	1
LUMP	word	0.19	4
LUND	nonword	0.30	3
LUNG	nonword	0.22	2
LUST	word	0.28	6
MAGD	word	0.20	4
MAGT	nonword	0.23	2
MAHT	nonword	0.26	3
MAIS	word	0.23	5
MANN	word	0.30	6
MANZ	nonword	0.23	2
MARS	word	0.26	5
MAUS	word	0.30	6
MEER	word	0.28	6
MEHL	word	0.27	5
MEIN	word	0.36	6
MELD	nonword	0.23	3
MELT	nonword	0.20	2
MEUR	nonword	0.19	1
MIEF	word	0.23	5
MIES	word	0.22	4
MILD	word	0.26	5
MILG	nonword	0.18	1
MILZ	word	0.26	5
MIST	word	0.28	6
MOHM	nonword	0.19	1
MOHN	word	0.27	5
MOND	word	0.24	5
MOOR	word	0.22	4
MOOS	word	0.22	4

items	lexicality	Msom	ops
MOOT	nonword	0.22	2
MORD	word	0.29	6
MORK	nonword	0.20	2
MORS	nonword	0.22	2
MUHR	nonword	0.20	2
MULS	nonword	0.21	2
MUND	word	0.32	6
NALL	nonword	0.25	3
NAMT	nonword	0.25	3
NANF	nonword	0.21	2
NARM	nonword	0.25	3
NARR	word	0.18	4
NATZ	nonword	0.22	2
NECH	nonword	0.23	3
NEER	nonword	0.23	3
NEID	word	0.24	5
NEIF	nonword	0.20	2
NEIM	nonword	0.26	3
NELL	nonword	0.22	2
NERV	word	0.20	4
NERZ	word	0.25	5
NEST	word	0.31	6
NETT	word	0.29	6
NETZ	word	0.24	5
NEUN	word	0.21	4
NEUT	nonword	0.20	2
NULL	word	0.20	4
NUNT	nonword	0.17	1
NURZ	nonword	0.21	2
OBST	word	0.18	4
PAAR	word	0.21	4
PAAT	nonword	0.24	3
PAKT	word	0.23	5
PARK	word	0.25	5
PAZT	nonword	0.30	3
PECH	word	0.18	4
PECK	nonword	0.33	3
PEIM	nonword	0.24	3
PELL	nonword	0.22	2
PELZ	word	0.20	4

items	lexicality	Msom	ops
PFAD	word	0.19	4
PFAU	word	0.19	4
PIEB	nonword	0.25	3
PILZ	word	0.24	5
PLAN	word	0.16	4
POHL	nonword	0.23	2
POST	word	0.27	6
PUCK	word	0.24	5
PULS	word	0.19	4
PULT	word	0.22	4
PUMP	word	0.18	4
PUND	nonword	0.30	3
PURT	nonword	0.26	3
PVEP	nonword	0.11	1
QUAL	word	0.15	4
QUER	word	0.17	4
QURG	nonword	0.15	1
RADT	nonword	0.26	3
RAHL	nonword	0.26	3
RAHM	word	0.27	5
RAPS	word	0.22	4
RARN	nonword	0.28	3
RAUB	word	0.29	6
RAUH	word	0.27	6
RAUM	word	0.31	6
REHL	nonword	0.21	2
REIM	word	0.30	6
REIS	word	0.29	6
REIZ	word	0.29	6
REST	word	0.31	6
RIFF	word	0.15	4
RING	word	0.26	5
RINK	nonword	0.25	3
RIPS	word	0.22	4
RITT	word	0.22	4
ROHR	word	0.23	4
RORF	nonword	0.24	3
RUHM	word	0.22	4
RUND	word	0.32	6
RUNG	nonword	0.25	3

items	lexicality	Msom	ops
RUPF	nonword	0.22	2
RURZ	nonword	0.17	1
SAAL	word	0.20	4
SACK	word	0.23	4
SAFT	word	0.29	6
SAHR	nonword	0.25	3
SALM	word	0.26	5
SALZ	word	0.25	5
SAMM	nonword	0.25	3
SAMT	word	0.25	5
SAND	word	0.32	6
SATT	word	0.29	6
SATZ	word	0.27	6
SAUC	nonword	0.31	3
SEET	nonword	0.24	3
SEHM	nonword	0.18	1
SEIL	word	0.33	6
SEKS	nonword	0.17	1
SEKT	word	0.24	5
SENF	word	0.20	4
SETT	nonword	0.29	3
SIEB	word	0.27	6
SIEG	word	0.23	5
SINN	word	0.25	5
SITZ	word	0.25	5
SKAT	word	0.22	4
SOCH	nonword	0.31	3
SOHN	word	0.26	5
SOUT	nonword	0.28	3
SPUR	word	0.22	4
SRAU	nonword	0.20	2
STAB	word	0.25	5
STAU	word	0.25	5
STIL	word	0.23	5
STOP	word	0.15	4
STUR	word	0.25	5
SUFF	word	0.25	5
TAGS	word	0.17	4
TAKT	word	0.25	5
TALG	word	0.25	5

items	lexicality	Msom	ops
TALZ	nonword	0.22	2
TANZ	word	0.28	6
TARM	nonword	0.25	3
TAUB	word	0.24	5
TAUD	nonword	0.31	3
TEIG	word	0.23	5
TEIL	word	0.31	6
TETT	nonword	0.27	3
TEXT	word	0.20	4
TIEF	word	0.23	5
TIER	word	0.31	6
TILZ	nonword	0.21	2
TOCH	nonword	0.29	3
TOLL	word	0.28	6
TOLZ	nonword	0.18	1
TORK	nonword	0.29	3
TRAM	word	0.26	5
TREU	word	0.17	4
TROG	word	0.19	4
TUMB	word	0.15	4
TURM	word	0.22	4
TURT	nonword	0.22	2
UNOM	nonword	0.13	1
URAT	nonword	0.18	1
VEID	nonword	0.19	1
VERB	word	0.25	5
VERS	word	0.20	4
VIEF	nonword	0.25	3
VIEH	word	0.25	5
VITZ	nonword	0.20	1
VOLK	word	0.22	4
WAHR	word	0.17	4
WALD	word	0.29	6
WAMS	word	0.29	6
WANF	nonword	0.20	2
WARM	word	0.20	4
WAUZ	nonword	0.26	3
WEDT	nonword	0.29	3
WEHL	nonword	0.26	3
WEIL	word	0.27	6

items	lexicality	Msom	ops
WEIT	word	0.34	6
WELM	nonword	0.34	3
WELT	word	0.21	4
WERK	word	0.30	6
WIFT	nonword	0.25	3
WILD	word	0.20	4
WIND	word	0.28	6
WINK	word	0.30	6
WIRT	word	0.25	5
WITZ	word	0.27	6
WOLF	word	0.23	4
WORF	nonword	0.20	2
WORT	word	0.24	5
WUND	word	0.30	6
WURF	word	0.33	6
WURM	word	0.20	4
WUST	nonword	0.25	3
XIER	nonword	0.26	3
ZAHL	word	0.29	6
ZAHN	word	0.29	6
ZANN	nonword	0.31	3
ZAPF	word	0.29	6
ZART	word	0.22	4
ZAUN	word	0.25	5
ZEHN	word	0.25	5
ZEIM	nonword	0.21	2
ZEIT	word	0.25	5
ZELD	nonword	0.27	3
ZELT	word	0.23	5
ZEUG	word	0.24	5
ZIEL	word	0.17	4
ZIMT	word	0.26	5
ZINS	word	0.17	4
ZOHR	nonword	0.26	3
ZOPF	word	0.21	4
ZORD	nonword	0.25	3
ZORN	word	0.26	5
ZORT	nonword	0.27	3
ZWAR	word	0.27	6
ZWEI	word	0.17	4

Note. Msom = summed global activity; ops = orthographic-phonological similiarity categories.

Appendix B. Pseudohomophones and Pseudowords of Study 2 and 3.

item	*group*	*letters*	*f group*	*frequency*	*big type*	*big token*	*n neigh*
AAN	*ph*	*3*	*low*	*1*	*6*	*2736*	*7*
AHL	*ph*	*3*	*low*	*13*	*3*	*18*	*5*
AHS	*ph*	*3*	*low*	*1*	*3*	*18*	*6*
AIS	*ph*	*3*	*low*	*10*	*3*	*1728*	*6*
AKD	*ph*	*3*	*high*	*50*	*1*	*51*	*1*
ALD	*ph*	*3*	*high*	*724*	*8*	*8228*	*8*
AMD	*ph*	*3*	*high*	*117*	*2*	*120*	*2*
ÄNG	*ph*	*3*	*high*	*155*	*1*	*155*	*1*
APT	*ph*	*3*	*low*	*13*	*0*	*0*	*7*
AXD	*ph*	*3*	*low*	*4*	*1*	*4*	*1*
BAI	*ph*	*3*	*high*	*2970*	*7*	*673*	*8*
BUP	*ph*	*3*	*low*	*5*	*5*	*21*	*5*
DOR	*ph*	*3*	*low*	*0*	*4*	*2608*	*6*
EIT	*ph*	*3*	*low*	*5*	*5*	*25155*	*5*
FEH	*ph*	*3*	*low*	*2*	*5*	*27*	*5*
HEI	*ph*	*3*	*low*	*2*	*3*	*3172*	*4*
HUD	*ph*	*3*	*high*	*33*	*2*	*38*	*2*
JOT	*ph*	*3*	*low*	*1*	*11*	*257*	*10*
KOD	*ph*	*3*	*low*	*1*	*3*	*173*	*3*
KUU	*ph*	*3*	*high*	*40*	*3*	*65*	*3*
LIT	*ph*	*3*	*low*	*4*	*3*	*8544*	*4*
LOD	*ph*	*3*	*low*	*2*	*7*	*297*	*8*
LOP	*ph*	*3*	*low*	*15*	*6*	*126*	*6*
MID	*ph*	*3*	*high*	*8539*	*5*	*8556*	*5*
NAA	*ph*	*3*	*high*	*56*	*2*	*77*	*2*
NOD	*ph*	*3*	*high*	*42*	*3*	*214*	*3*
OOR	*ph*	*3*	*high*	*49*	*3*	*2584*	*4*
ORD	*ph*	*3*	*high*	*112*	*1*	*112*	*1*
REE	*ph*	*3*	*low*	*5*	*6*	*97*	*6*
ROD	*ph*	*3*	*high*	*109*	*6*	*435*	*7*
ROO	*ph*	*3*	*low*	*20*	*5*	*278*	*5*
TAD	*ph*	*3*	*high*	*122*	*9*	*1212*	*10*
TEH	*ph*	*3*	*low*	*13*	*4*	*37*	*4*
TIB	*ph*	*3*	*low*	*16*	*2*	*17*	*3*
TYB	*ph*	*3*	*high*	*54*	*1*	*54*	*2*
UNT	*ph*	*3*	*high*	*25085*	*3*	*25907*	*3*
WEE	*ph*	*3*	*low*	*16*	*7*	*1036*	*8*
WEK	*ph*	*3*	*high*	*425*	*3*	*945*	*3*
WUD	*ph*	*3*	*low*	*13*	*1*	*13*	*1*
ZEE	*ph*	*3*	*low*	*3*	*6*	*95*	*6*

item	*group*	*letters*	*f group*	*frequency*	*big type*	*big token*	*n neigh*
ZOH	*ph*	*3*	*low*	*15*	*2*	*36*	*4*
ZUK	*ph*	*3*	*high*	*120*	*1*	*121*	*1*
BALT	*ph*	*4*	*high*	*159*	*51*	*2963*	*7*
BIHR	*ph*	*4*	*high*	*46*	*14*	*4458*	*1*
EKKE	*ph*	*4*	*low*	*0*	*8*	*15*	*1*
FLUK	*ph*	*4*	*high*	*35*	*21*	*382*	*5*
FOLL	*ph*	*4*	*high*	*280*	*42*	*2438*	*8*
GIHR	*ph*	*4*	*low*	*3*	*14*	*4131*	*1*
GURD	*ph*	*4*	*low*	*2*	*22*	*710*	*2*
HALD	*ph*	*4*	*high*	*45*	*62*	*3743*	*11*
HEEL	*ph*	*4*	*low*	*3*	*35*	*3908*	*4*
HELT	*ph*	*4*	*high*	*43*	*41*	*3775*	*7*
JAAR	*ph*	*4*	*high*	*2145*	*18*	*3424*	*4*
KAAL	*ph*	*4*	*low*	*10*	*32*	*858*	*2*
KLEH	*ph*	*4*	*low*	*2*	*16*	*366*	*2*
KRUK	*ph*	*4*	*low*	*5*	*14*	*77*	*1*
LEIE	*ph*	*4*	*low*	*15*	*54*	*27030*	*7*
LIET	*ph*	*4*	*high*	*48*	*35*	*5085*	*4*
LUFD	*ph*	*4*	*high*	*108*	*15*	*299*	*2*
MAGT	*ph*	*4*	*low*	*4*	*29*	*1574*	*4*
MOHS	*ph*	*4*	*low*	*4*	*23*	*786*	*4*
PAHR	*ph*	*4*	*high*	*26*	*39*	*7532*	*4*
PARG	*ph*	*4*	*high*	*35*	*41*	*1084*	*5*
PFAT	*ph*	*4*	*low*	*5*	*11*	*46*	*2*
ROSD	*ph*	*4*	*low*	*4*	*16*	*216*	*3*
RUNT	*ph*	*4*	*high*	*250*	*28*	*1703*	*3*
SAHL	*ph*	*4*	*high*	*41*	*51*	*4363*	*6*
SARK	*ph*	*4*	*low*	*16*	*52*	*1711*	*6*
TEHR	*ph*	*4*	*low*	*1*	*30*	*6680*	*4*
TROK	*ph*	*4*	*low*	*0*	*22*	*1913*	*2*
WAAL	*ph*	*4*	*high*	*163*	*36*	*1091*	*3*
WANT	*ph*	*4*	*high*	*49*	*52*	*7381*	*5*
WASE	*ph*	*4*	*low*	*6*	*46*	*1357*	*8*
WELD	*ph*	*4*	*high*	*979*	*44*	*8631*	*7*
WERG	*ph*	*4*	*high*	*251*	*40*	*7935*	*3*
WUNT	*ph*	*4*	*low*	*6*	*22*	*1308*	*2*
ZAIT	*ph*	*4*	*high*	*1032*	*20*	*3191*	*2*
ZELD	*ph*	*4*	*low*	*10*	*33*	*3919*	*4*
ZEUK	*ph*	*4*	*high*	*39*	*10*	*1852*	*1*
ZIHL	*ph*	*4*	*high*	*257*	*18*	*1174*	*2*

item	*group*	*letters*	*f group*	*frequency*	*big type*	*big token*	*n neigh*
BAIDE	*ph*	*5*	*high*	*783*	*93*	*2492*	*3*
BAKKE	*ph*	*5*	*low*	*0*	*93*	*800*	*3*
BIHNE	*ph*	*5*	*low*	*7*	*79*	*2845*	*4*
DAMID	*ph*	*5*	*high*	*815*	*49*	*5121*	*1*
DOCHD	*ph*	*5*	*low*	*1*	*62*	*10394*	*1*
DRAAT	*ph*	*5*	*low*	*11*	*83*	*3276*	*1*
DURSD	*ph*	*5*	*low*	*10*	*42*	*5058*	*1*
ECKSE	*ph*	*5*	*low*	*2*	*59*	*685*	*1*
ELENT	*ph*	*5*	*low*	*7*	*32*	*1234*	*1*
ERPSE	*ph*	*5*	*low*	*2*	*65*	*2140*	*1*
FATER	*ph*	*5*	*high*	*234*	*238*	*13630*	*4*
FOGEL	*ph*	*5*	*high*	*39*	*158*	*7595*	*1*
GAIST	*ph*	*5*	*high*	*114*	*78*	*1553*	*1*
GRAIS	*ph*	*5*	*low*	*7*	*79*	*3082*	*2*
GRUNT	*ph*	*5*	*high*	*437*	*55*	*1919*	*1*
HILVE	*ph*	*5*	*high*	*215*	*42*	*805*	*1*
KEELE	*ph*	*5*	*low*	*10*	*74*	*991*	*4*
KLAIN	*ph*	*5*	*high*	*576*	*75*	*2230*	*1*
KLEIT	*ph*	*5*	*high*	*41*	*59*	*3844*	*2*
KRAFD	*ph*	*5*	*high*	*354*	*75*	*3189*	*1*
KRAIS	*ph*	*5*	*high*	*274*	*93*	*3701*	*2*
KURTZ	*ph*	*5*	*high*	*378*	*58*	*3300*	*0*
LEENE	*ph*	*5*	*low*	*3*	*96*	*5101*	*3*
LENGE	*ph*	*5*	*high*	*33*	*116*	*5891*	*7*
MACHD	*ph*	*5*	*high*	*174*	*111*	*11449*	*2*
NIHTE	*ph*	*5*	*low*	*2*	*98*	*11227*	*1*
PFAAL	*ph*	*5*	*low*	*1*	*44*	*976*	*1*
PFANT	*ph*	*5*	*low*	*1*	*40*	*553*	*1*
PRAIS	*ph*	*5*	*high*	*264*	*79*	*2868*	*1*
RAISE	*ph*	*5*	*high*	*46*	*104*	*1368*	*3*
SIRUB	*ph*	*5*	*low*	*1*	*46*	*873*	*1*
SPIHL	*ph*	*5*	*high*	*203*	*51*	*959*	*2*
STAAL	*ph*	*5*	*high*	*35*	*101*	*5431*	*3*
STAHT	*ph*	*5*	*high*	*494*	*98*	*13688*	*5*
STARG	*ph*	*5*	*high*	*481*	*85*	*5212*	*3*
WENUS	*ph*	*5*	*low*	*15*	*92*	*3528*	*1*
WESDE	*ph*	*5*	*high*	*31*	*88*	*2993*	*4*
ZWEKK	*ph*	*5*	*high*	*55*	*15*	*287*	*1*
ZWERK	*ph*	*5*	*low*	*3*	*32*	*959*	*2*
ZWISD	*ph*	*5*	*low*	*1*	*31*	*545*	*1*

item	*group*	*letters*	*f group*	*frequency*	*big type*	*big token*	*n neigh*
ALN	*pw*	*3*	*low*	*1*	*8*	*8228*	*9*
ARL	*pw*	*3*	*low*	*13*	*4*	*465*	*6*
APS	*pw*	*3*	*low*	*1*	*0*	*0*	*3*
OIS	*pw*	*3*	*low*	*10*	*2*	*1727*	*2*
AKS	*pw*	*3*	*high*	*50*	*1*	*51*	*4*
ALZ	*pw*	*3*	*high*	*724*	*8*	*8228*	*8*
AMK	*pw*	*3*	*high*	*117*	*2*	*120*	*3*
ANG	*pw*	*3*	*high*	*155*	*1*	*155*	*2*
AFT	*pw*	*3*	*low*	*13*	*1*	*219*	*8*
AXG	*pw*	*3*	*low*	*4*	*1*	*4*	*2*
BER	*pw*	*3*	*high*	*2970*	*5*	*123304*	*8*
BUF	*pw*	*3*	*low*	*5*	*7*	*7472*	*7*
ZOR	*pw*	*3*	*low*	*0*	*4*	*2599*	*5*
EIP	*pw*	*3*	*low*	*5*	*4*	*16631*	*4*
FEU	*pw*	*3*	*low*	*2*	*5*	*1366*	*5*
WAI	*pw*	*3*	*low*	*2*	*4*	*2219*	*4*
HUS	*pw*	*3*	*high*	*33*	*6*	*3908*	*6*
JOL	*pw*	*3*	*low*	*1*	*6*	*140*	*6*
KOK	*pw*	*3*	*low*	*1*	*2*	*20*	*2*
KUP	*pw*	*3*	*high*	*40*	*4*	*66*	*4*
LIN	*pw*	*3*	*low*	*4*	*4*	*16854*	*4*
LUT	*pw*	*3*	*low*	*2*	*7*	*1471*	*8*
LOF	*pw*	*3*	*low*	*15*	*6*	*204*	*6*
MIL	*pw*	*3*	*high*	*8539*	*3*	*8547*	*5*
NAF	*pw*	*3*	*high*	*56*	*2*	*77*	*2*
NOL	*pw*	*3*	*high*	*42*	*4*	*173*	*4*
ORR	*pw*	*3*	*high*	*49*	*1*	*112*	*2*
ORL	*pw*	*3*	*high*	*112*	*1*	*112*	*1*
RET	*pw*	*3*	*low*	*5*	*4*	*9*	*6*
SOT	*pw*	*3*	*high*	*109*	*10*	*250*	*11*
ROL	*pw*	*3*	*low*	*20*	*7*	*394*	*7*
LAT	*pw*	*3*	*high*	*122*	*5*	*507*	*6*
TEI	*pw*	*3*	*low*	*13*	*2*	*2984*	*2*
TIF	*pw*	*3*	*low*	*16*	*2*	*17*	*2*
TUP	*pw*	*3*	*high*	*54*	*2*	*597*	*4*
IND	*pw*	*3*	*high*	*25085*	*1*	*25185*	*1*
WEF	*pw*	*3*	*low*	*16*	*3*	*945*	*3*
DEG	*pw*	*3*	*high*	*425*	*3*	*120183*	*3*
WUK	*pw*	*3*	*low*	*13*	*1*	*13*	*1*
ZER	*pw*	*3*	*low*	*3*	*6*	*120337*	*7*

item	*group*	*letters*	*f group*	*frequency*	*big type*	*big token*	*n neigh*
LOR	*pw*	*3*	*low*	*15*	*4*	*2599*	*5*
ZUB	*pw*	*3*	*high*	*120*	*2*	*126*	*2*
BALF	*pw*	*4*	*high*	*159*	*45*	*1870*	*3*
BIRR	*pw*	*4*	*high*	*46*	*16*	*1099*	*2*
EFKE	*pw*	*4*	*low*	*0*	*8*	*12*	*1*
FLUM	*pw*	*4*	*high*	*35*	*27*	*949*	*5*
VORL	*pw*	*4*	*high*	*280*	*32*	*2556*	*2*
GIRR	*pw*	*4*	*low*	*3*	*16*	*772*	*3*
GURS	*pw*	*4*	*low*	*2*	*18*	*656*	*3*
HALN	*pw*	*4*	*high*	*45*	*50*	*2887*	*8*
HERL	*pw*	*4*	*low*	*3*	*38*	*2901*	*8*
HELS	*pw*	*4*	*high*	*43*	*36*	*2708*	*5*
JAHL	*pw*	*4*	*high*	*2145*	*34*	*6193*	*6*
NAHL	*pw*	*4*	*low*	*10*	*40*	*8199*	*7*
KLET	*pw*	*4*	*low*	*2*	*17*	*358*	*2*
KRUT	*pw*	*4*	*low*	*5*	*20*	*307*	*2*
NAIE	*pw*	*4*	*low*	*15*	*23*	*4292*	*6*
LIEM	*pw*	*4*	*high*	*48*	*38*	*5105*	*2*
LUFP	*pw*	*4*	*high*	*108*	*15*	*299*	*2*
MAGF	*pw*	*4*	*low*	*4*	*28*	*1572*	*1*
MONS	*pw*	*4*	*low*	*4*	*23*	*992*	*3*
PLAR	*pw*	*4*	*high*	*26*	*20*	*1826*	*3*
PARP	*pw*	*4*	*high*	*35*	*36*	*978*	*4*
PFAK	*pw*	*4*	*low*	*5*	*7*	*19*	*2*
ROSK	*pw*	*4*	*low*	*4*	*16*	*216*	*4*
REND	*pw*	*4*	*high*	*250*	*45*	*6539*	*3*
SART	*pw*	*4*	*high*	*41*	*60*	*2458*	*11*
NARG	*pw*	*4*	*low*	*16*	*40*	*5022*	*3*
TEIR	*pw*	*4*	*low*	*1*	*52*	*27286*	*3*
TROF	*pw*	*4*	*low*	*0*	*22*	*1913*	*2*
WAUL	*pw*	*4*	*high*	*163*	*47*	*1955*	*5*
WANF	*pw*	*4*	*high*	*49*	*53*	*7683*	*3*
VOSE	*pw*	*4*	*low*	*6*	*31*	*1301*	*5*
WELN	*pw*	*4*	*high*	*979*	*32*	*7775*	*4*
WERZ	*pw*	*4*	*high*	*251*	*42*	*8660*	*5*
GUND	*pw*	*4*	*low*	*6*	*40*	*3900*	*9*
ZEIF	*pw*	*4*	*high*	*1032*	*46*	*28168*	*2*
RELT	*pw*	*4*	*low*	*10*	*36*	*3172*	*3*
ZEUL	*pw*	*4*	*high*	*39*	*12*	*1870*	*1*
ZIRL	*pw*	*4*	*high*	*257*	*15*	*396*	*1*

item	*group*	*letters*	*f group*	*frequency*	*big type*	*big token*	*n neigh*
BEFDE	*pw*	*5*	*high*	*783*	*70*	*2188*	*1*
BAZKE	*pw*	*5*	*low*	*0*	*85*	*749*	*3*
BIANE	*pw*	*5*	*low*	*7*	*94*	*3000*	*3*
DAMIL	*pw*	*5*	*high*	*815*	*55*	*5358*	*2*
DOCHG	*pw*	*5*	*low*	*1*	*62*	*10394*	*1*
DRALT	*pw*	*5*	*low*	*11*	*77*	*1983*	*3*
DURSG	*pw*	*5*	*low*	*10*	*42*	*5058*	*1*
ECHRE	*pw*	*5*	*low*	*2*	*60*	*2208*	*1*
EREND	*pw*	*5*	*low*	*7*	*64*	*3479*	*2*
ERNSE	*pw*	*5*	*low*	*2*	*79*	*2845*	*3*
VITER	*pw*	*5*	*high*	*234*	*215*	*12993*	*4*
SOGEL	*pw*	*5*	*high*	*39*	*166*	*9194*	*3*
GELST	*pw*	*5*	*high*	*114*	*100*	*6760*	*1*
GRUIS	*pw*	*5*	*low*	*7*	*50*	*2134*	*1*
GRIND	*pw*	*5*	*high*	*437*	*82*	*4506*	*1*
HILGE	*pw*	*5*	*high*	*215*	*77*	*2638*	*2*
KEHNE	*pw*	*5*	*low*	*10*	*85*	*5345*	*4*
KLEUN	*pw*	*5*	*high*	*576*	*35*	*1505*	*1*
KLEIG	*pw*	*5*	*high*	*41*	*103*	*4529*	*2*
KRAFL	*pw*	*5*	*high*	*354*	*75*	*3189*	*2*
KRELS	*pw*	*5*	*high*	*274*	*63*	*2291*	*2*
KURNZ	*pw*	*5*	*high*	*378*	*41*	*2878*	*0*
LESNE	*pw*	*5*	*low*	*3*	*94*	*5148*	*2*
LINGE	*pw*	*5*	*high*	*33*	*117*	*7568*	*10*
MACHG	*pw*	*5*	*high*	*174*	*111*	*11449*	*2*
NILTE	*pw*	*5*	*low*	*2*	*123*	*11691*	*1*
PFARL	*pw*	*5*	*low*	*1*	*28*	*755*	*1*
PFANK	*pw*	*5*	*low*	*1*	*45*	*507*	*1*
PRELS	*pw*	*5*	*high*	*264*	*49*	*1458*	*1*
RELSE	*pw*	*5*	*high*	*46*	*102*	*1970*	*2*
SIRUL	*pw*	*5*	*low*	*1*	*49*	*859*	*1*
SPIRL	*pw*	*5*	*high*	*203*	*49*	*760*	*2*
STAUL	*pw*	*5*	*high*	*35*	*91*	*4822*	*3*
STAST	*pw*	*5*	*high*	*494*	*119*	*5830*	*5*
STORK	*pw*	*5*	*high*	*481*	*74*	*3523*	*3*
VETUS	*pw*	*5*	*low*	*15*	*72*	*2292*	*2*
WESGE	*pw*	*5*	*high*	*31*	*83*	*3599*	*2*
ZWELK	*pw*	*5*	*high*	*55*	*21*	*386*	*1*
ZWIRG	*pw*	*5*	*low*	*3*	*18*	*235*	*2*
ZWISP	*pw*	*5*	*low*	*1*	*31*	*545*	*1*

Note. group = stimulus category: pw = pseudoword, ph = pseudohomophone; letters = number of letters; syl = number of syllables; f-group = frequency category; frequency = the number of times the baseword appears in 1 million words in print and speech; n neigh = number of orthographic neighbours; big token = sum of all frequencies of the words which contain one or more bigrams of stimulus; big type = number of times the bigrams of a given word are appears in the German CELEX lemma database.

Appendix C. Word Stimuli of Study 2 and 3

item	group	letters	syll	freq	f group	neigh	f neigh	hf neigh	big type
AHA	filler	3	2	16	high	3	2	0	4
AHM	filler	3	1	0	low	5	177	5	5
ALL	filler	3	1	2664	high	8	5565	1	9
ARA	filler	3	2	1	low	4	480	4	5
AUF	word	3	1	7350	high	4	3960	0	6
BÖE	filler	3	2	1	low	1	25	1	0
DES	word	3	1	0	low	2	109669	1	4
DUO	word	3	2	1	low	1	1	0	3
EGO	word	3	2	0	low	0	0	0	2
GAU	filler	3	1	3	low	8	636	7	10
HAB	word	3	1	1	low	5	137	5	7
ICH	word	3	1	7126	high	1	78	0	3
IHR	filler	3	1	2270	high	3	781	0	5
JAK	word	3	1	0	low	3	0	0	5
JUX	filler	3	1	1	low	2	8	2	4
LAU	filler	3	1	3	low	8	511	4	9
LEE	word	3	1	3	low	4	88	2	6
LUG	word	3	1	1	low	5	130	4	6
LUV	filler	3	1	0	low	2	7	2	4
LUX	word	3	1	6	low	4	3	0	5
MOL	word	3	1	2	low	4	617	2	5
MUS	word	3	1	6	low	5	3904	3	7
NEU	filler	3	1	1357	high	2	5	0	4
PUR	word	3	1	4	low	5	2940	3	6
RAN	word	3	1	0	low	7	2879	7	7
RAR	word	3	1	3	low	7	563	5	9
RUM	filler	3	1	8	low	5	204	2	6
SAU	filler	3	1	3	low	6	241	2	7
SEX	word	3	1	5	low	2	73	1	4
SIE	word	3	1	9491	high	4	3974	0	5
HAU	word	3	1	104	high	10	177	1	11
ULK	word	3	1	0	low	1	1	1	3
VON	word	3	1	9312	high	5	2531	0	7
WIE	filler	3	1	3575	high	3	13941	2	5
YEN	word	3	1	2	low	3	4	1	5
ZEN	word	3	1	0	low	4	9	4	6
AFFE	word	4	2	7	low	0	0	0	7
ALTE	word	4	2	63	high	5	546	1	28
ATEM	filler	4	2	25	high	2	19	0	14
AUGE	filler	4	2	302	high	3	6	0	26

item	group	letters	syll	freq	f group	neigh	f neigh	hf neigh	big type
AUTO	word	4	2	115	high	0	0	0	17
BEET	word	4	1	2	low	3	244	3	19
BETT	word	4	1	118	high	10	192	1	34
BLUT	word	4	1	43	high	3	19	0	25
BOOT	word	4	1	26	high	2	32	1	16
BREI	filler	4	1	3	low	3	921	3	20
DACH	filler	4	1	34	high	6	4938	3	40
DUFT	word	4	1	10	low	2	108	1	23
EHRE	filler	4	2	70	high	2	1527	1	19
EILE	word	4	2	11	low	4	5	0	26
ESEL	word	4	2	12	high	3	22	1	16
EULE	word	4	2	2	low	4	14	2	26
FARM	word	4	1	6	low	5	284	2	48
FELD	filler	4	1	100	high	4	262	1	40
FELS	filler	4	1	12	high	2	105	1	30
FETE	filler	4	2	0	low	3	29	1	43
FLUT	filler	4	1	14	high	5	136	3	27
FUNK	filler	4	1	18	high	2	20	1	31
HANF	word	4	1	1	low	3	624	3	60
HAST	word	4	1	6	low	11	626	8	63
KALK	filler	4	1	4	low	4	97	3	42
KEIM	word	4	1	8	low	6	1304	2	52
KINO	filler	4	2	25	high	3	443	1	32
KORN	word	4	1	8	low	8	138	5	53
KULT	word	4	1	2	low	5	87	2	30
MARS	filler	4	1	9	low	3	361	2	46
NARR	word	4	1	5	low	0	0	0	39
NERZ	word	4	1	1	low	3	196	3	37
OFEN	filler	4	2	10	low	2	116	1	18
PACK	filler	4	1	1	low	6	59	4	41
PILZ	word	4	1	5	low	3	5	0	26
RAHM	filler	4	1	1	low	6	250	4	44
RATE	word	4	2	9	low	6	10	0	49
SALZ	filler	4	1	11	high	3	164	1	53
SENF	filler	4	1	4	low	2	63	1	23
TEST	filler	4	1	11	low	7	694	5	45
WALD	word	4	1	80	high	6	279	1	55
ZORN	filler	4	1	22	high	4	70	1	45
AMPEL	word	5	2	2	low	1	1	0	99
BARON	word	5	2	9	low	1	3	0	109

item	group	letters	syll	freq	f group	neigh	f neigh	hf neigh	big type
BAUCH	word	5	1	15	high	4	43	1	120
DAMPF	word	5	1	6	low	2	349	2	51
DRECK	word	5	1	8	low	2	102	1	74
DRUCK	word	5	1	101	high	2	8	0	68
ENKEL	filler	5	2	11	high	2	55	2	116
FALKE	word	5	2	6	low	4	38	1	114
FLUCH	word	5	1	6	low	1	32	1	81
FRIST	word	5	1	19	high	3	15	0	102
GEBET	filler	5	2	11	low	4	1731	2	112
GLANZ	word	5	1	19	high	0	0	0	53
GRUBE	filler	5	2	20	high	1	0	0	65
HALLE	word	5	2	37	high	7	82	0	143
HENNE	filler	5	2	6	low	4	4	0	122
IMKER	filler	5	2	1	low	1	1153	1	168
JACKE	word	5	2	0	low	6	0	0	109
KADER	word	5	2	15	high	6	14	0	233
KATER	word	5	2	10	low	5	255	2	249
KERZE	word	5	2	10	low	2	28	1	70
KLAGE	word	5	2	28	high	3	7	0	89
KOBRA	word	5	2	2	low	0	0	0	51
KRANZ	word	5	1	16	high	2	37	1	97
LABOR	filler	5	2	6	low	0	0	0	66
LAKEN	filler	5	2	1	low	4	72	2	242
LATTE	filler	5	2	3	low	6	17	3	172
LICHT	word	5	1	109	high	6	8055	1	101
LUNGE	word	5	2	7	low	6	267	4	89
MESSE	word	5	2	36	high	2	69	1	95
MOTOR	filler	5	2	94	high	1	1	0	75
NUDEL	filler	5	2	1	low	4	10	3	145
OPFER	filler	5	2	111	high	0	0	0	153
ORKAN	filler	5	2	1	low	1	55	1	45
PANIK	word	5	2	7	low	0	0	0	85
PFERD	word	5	1	65	high	0	0	0	30
PUDEL	word	5	2	2	low	4	4	1	153
SALAT	word	5	2	6	low	1	5	0	96
SONDE	word	5	2	5	low	3	104	2	106
TAUFE	filler	5	2	8	low	2	13	1	76
TONNE	filler	5	2	74	high	6	108	1	111
TUMOR	word	5	2	1	low	3	15	2	57
WAFFE	filler	5	2	80	high	0	0	0	42

item	group	letters	syll	freq	f group	neigh	f neigh	hf neigh	big type
WANNE	word	5	2	5	low	6	30	2	124
WODKA	filler	5	2	4	low	0	0	0	38
WOLLE	word	5	2	23	high	7	300	3	124
BAU	word	3	1	129	high	9	312	1	11
BIS	filler	3	1	1716	high	5	4817	0	5
EIN	word	3	1	16599	high	4	26533	0	6
GAR	word	3	1	361	high	7	8633	0	9
HER	word	3	1	196	high	4	110142	2	6
HIN	filler	3	1	248	high	2	16602	1	4
MAL	filler	3	1	487	high	7	323733	1	8
MAN	word	3	1	2716	high	5	96767	0	7
NUN	filler	3	1	817	high	4	347617	1	6
NUR	filler	3	1	2875	high	5	83783	0	7
POL	filler	3	1	128	high	3	317	0	5
TUN	filler	3	1	596	high	3	877	1	4
UND	filler	3	1	25085	high	2	72167	0	4
UNS	filler	3	1	718	high	2	25088	1	4
WAS	filler	3	1	1867	high	3	38	0	5
WER	filler	3	1	416	high	6	1145955	3	7
ALM	word	3	1	1	low	9	837383	7	9
AUE	word	3	2	9	low	6	1120117	2	4
DIA	filler	3	2	2	low	1	267	1	3
DUR	word	3	1	1	low	5	11256167	5	6
GEL	word	3	1	1	low	1	3	1	3
HEU	filler	3	1	5	low	4	165683	3	5
HUF	word	3	1	5	low	4	755867	4	5
KLO	filler	3	1	1	low	0	0	0	2
MOP	word	3	1	0	low	1	183	1	3
ODE	word	3	2	4	low	2	233	0	4
OMA	word	3	2	7	low	1	967	1	2
OPA	word	3	2	10	low	1	733	0	2
TAU	filler	3	1	3	low	10	125217	6	12
UHU	filler	3	2	0	low	1	7325	1	3
WAL	filler	3	1	6	low	4	239133	4	6
ZAR	filler	3	1	7	low	4	40383	2	6
ALP	word	3	1	18	high	7	819817	3	9
DOM	filler	3	1	24	high	1	10467	1	3
GAS	word	3	1	32	high	5	223283	2	7
HOF	filler	3	1	79	high	1	5	0	2
LOK	filler	3	1	19	high	4	10483	1	6

item	group	letters	syll	freq	f group	neigh	f neigh	hf neigh	big type
RUF	filler	3	1	96	high	5	736617	1	7
SEE	filler	3	1	73	high	6	951433	1	7
TAL	filler	3	1	24	high	8	149533	3	10
TON	filler	3	1	59	high	8	10265	5	9
RAD	word	3	1	43	high	5	26933	2	7
TOT	filler	3	1	78	high	2	722	0	12
BANK	filler	4	1	228	high	9	19517	0	61
DING	filler	4	1	238	high	2	465	0	40
ENDE	filler	4	2	374	high	3	21667	0	22
FORM	filler	4	1	226	high	3	12217	0	41
HAND	filler	4	1	472	high	10	126217	1	78
KOPF	filler	4	1	230	high	2	1717	0	27
LAGE	filler	4	2	296	high	10	795	0	49
SEHR	filler	4	1	969	high	3	82167	0	29
SEIT	filler	4	1	583	high	5	2151817	3	52
SINN	filler	4	1	284	high	3	3667	0	43
WORT	filler	4	1	458	high	7	75367	0	45
ZEIT	filler	4	1	1034	high	3	163683	1	48
BOJE	word	4	2	0	low	1	2	1	11
EBBE	word	4	2	3	low	2	2667	1	19
FANG	filler	4	1	3	low	8	696	5	58
FILZ	word	4	1	1	low	3	14017	3	25
HAIN	filler	4	1	1	low	3	145	1	51
HEFE	word	4	2	1	low	3	2933	2	25
HELM	word	4	1	4	low	4	12983	3	41
HEXE	word	4	2	6	low	3	117	0	26
KAMM	word	4	1	8	low	4	28417	2	32
KANU	word	4	2	0	low	0	0	0	47
LAMM	word	4	1	3	low	5	2767	3	38
LAUS	word	4	1	2	low	9	55517	7	58
WURM	word	4	1	4	low	3	7733	3	26
BERG	word	4	1	67	high	2	1667	0	33
HAUT	word	4	1	49	high	7	62267	3	58
KERN	word	4	1	32	high	5	149367	3	39
KNIE	word	4	1	37	high	0	0	0	7
LAST	filler	4	1	35	high	9	49267	3	58
LOCH	filler	4	1	31	high	6	523633	3	43
MEER	word	4	1	70	high	4	883	1	39
NOTE	filler	4	2	46	high	8	52	1	41
OPER	filler	4	2	45	high	2	220933	1	30

item	group	letters	syll	freq	f group	neigh	f neigh	hf neigh	big type
RAND	word	4	1	59	high	11	181817	4	74
RING	word	4	1	46	high	3	3095	2	41
WARE	filler	4	2	60	high	4	6017	0	56
WIND	filler	4	1	62	high	7	55033	1	49
APRIL	filler	5	2	239	high	0	0	0	52
DABEI	filler	5	2	512	high	1	0	0	84
DAVON	filler	5	2	348	high	2	2883	0	53
FOLGE	filler	5	2	165	high	2	533	0	82
JUNGE	word	5	2	130	high	2	2267	0	88
LEBEN	filler	5	2	865	high	11	253117	1	280
METER	filler	5	2	210	high	3	10733	0	225
NATUR	filler	5	2	118	high	1	0	0	71
RECHT	filler	5	1	431	high	1	233	0	105
BELAG	word	5	2	1	low	1	25	1	58
GEIER	word	5	2	3	low	6	1683	1	245
HECHT	word	5	1	2	low	1	43067	1	100
KEHLE	filler	5	2	10	low	6	3133	1	86
KOMET	word	5	2	3	low	0	0	0	57
LACHS	filler	5	1	0	low	4	1817	3	105
QUARK	filler	5	1	1	low	2	133	1	37
RINNE	filler	5	2	1	low	4	75	2	123
SAHNE	filler	5	2	6	low	3	33	1	92
SAITE	word	5	2	2	low	1	63667	1	134
STIEL	word	5	1	3	low	3	26617	3	167
TABAK	word	5	2	8	low	0	0	0	54
UNFUG	filler	5	2	5	low	0	0	0	29
WAISE	filler	5	2	1	low	1	1933	1	96
BLUME	filler	5	2	32	high	1	633	0	55
DAUER	filler	5	2	53	high	5	40483	2	199
ENGEL	word	5	2	32	high	3	4533	0	151
FAUST	filler	5	1	36	high	0	0	0	104
FIGUR	word	5	2	43	high	0	0	0	40
FISCH	filler	5	1	34	high	3	10083	1	84
KARTE	word	5	2	47	high	4	2367	0	181
LESER	filler	5	2	59	high	6	1925	1	209
MALER	word	5	2	33	high	5	9067	1	229
STAMM	filler	5	1	35	high	1	175	0	85
STOFF	filler	5	1	51	high	0	0	0	72
STROM	filler	5	1	54	high	1	433	0	74
TRAUM	filler	5	1	38	high	1	333	0	112

Note. group = stimulus category; letters = number of letters; syl = number of syllables; f-group = frequency category; neigh = number of orthographic neighbours; f neigh = summed frequency of orthographic neighbours; hf neigh = number of higher frequency neighbours; big type = number of times the bigrams of a given word are appears in the German CELEX lemma database.

Erklärung

Hiermit versichere ich, die vorliegende Arbeit selbständig und ohne Verwendung anderer als der angegebenen Hilfsmittel erstellt und verfaßt zu haben. Die vorliegende Arbeit war nicht Gegenstand eines früheren Promotionsverfahrens. Die einzelnen Kapitel dieser Dissertationsschrift wurden in marginal modifizierten Versionen in internationalen Fachzeitschriften veröffentlicht, zur Veröffentlichung angenommen oder befinden sich im Review Prozess.

Studie 1 ist im Jahre 2006 in der Zeitschrift 'Brain Research', Ausgabe 1073-1074, Seiten 431-439 erschienen. Koautoren sind: Arthur, M. Jacobs, Anja Hahne, Brigitte Ricker, Markus Hofmann und Florian Hutzler.

Studie 2 erscheint im Jahre 2009 in der Zeitschrift 'Human Brain Mapping' Nummer der Ausgabe und Seitenzahlen sind noch nicht verfügbar. Der Artikel wurde am 30. Juli 2008 zur Veröffentlichung angenommen und am 22. August 2008 im Internetauftritt der Zeitschrift veröffentlicht. Koautoren sind: Florian Hutzler, Johannes C. Ziegler, Michael Dambacher und Arthur M. Jacobs.

Studie 3 ist unter Review in der Zeitschrift 'Journal of Cognitive Neuroscience'. Koautoren sind: Florian Hutzler, Thomas F. Münte, Michael Rotte, Michael Dambacher und Arthur M. Jacobs.

Alle Koautoren können bestätigen, dass ich sowohl für die Planung, Durchführung und Auswertung der Experimente als auch für das Verfassen der Artikel dieser Dissertationsschrift allein - oder hauptverantwortlich war.

Berlin, den 20. Januar 2009

Mario Braun